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YIELD OF ELECTRONIC MATERIALS AND DEVICES

PREPARED BY THE AD HOC
PANEL ON YIELD OF ELECTRONIC MATERIALS AND DEVICES
OF THE
AD HOC COMMITTEE ON MATERIALS AND PROCESSES FOR ELECTRON DEVICES

NATIONAL MATERIALS ADVISORY BOARD
DIVISION OF ENGINEERING - NATIONAL RESEARCH COUNCIL

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NOTICE

The study reported herein was undertaken under the aegis of the National Research Council with the express approval of the Governing Board of the National Research Council. Such approval indicated that the Board considered that the problem is of national significance; that elucidation or solution of the problem required scientific or technical competence and that the resources of the National Research Council were particularly suitable to the conduct of the project. The institutional responsibilities of the National Research Council were then discharged in the following manner:

> The members of the study committee were selected for their individual scholarly competence and judgment with due consideration for the balance and breadth of disciplines. Responsibility for all aspects of this report rests with the study committee, to whom sincere appreciation is expressed.
>
> Although the reports of our study committees are not submitted for approval to the Academy membership or to the Council, each report is reviewed by a second group of appropriately qualified individuals according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine, *inter alia*, whether the major questions and relevant points of view have been addressed and whether the reported findings, conclusions, and recommendations arose from the available data and information. Distribution of the report is approved by the President only after satisfactory completion of this review process.

This study, by the National Materials Advisory Board, was conducted under Contract No. DA-49-083 OSA3131 with the Department of Defense.

Members of the National Materials Advisory Board study groups serve as individuals contributing their personal knowledge and judgments and not as representatives of any organization in which they are employed or with which they may be associated.

The quantitative data published in this report are intended only to illustrate the scope and substance of information considered in the study, and should not be used for any other purpose, such as in specifications or in design, unless so stated.

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Dr. I. Arnold Lesk, Director, Central Research Laboratories, Semiconductor Products Division, Motorola, Inc., Phoenix, Arizona, 85008

Mr. Jerome J. Suran, Manager, Electronic Applications and Devices, General Electric Company, Electronics Park, Syracuse, New York, 13201

Dr. Max T. Weiss, Head, Electronics Division, Aerospace Corporation, P. O. Box 95085, El Segundo, California, 90045

NMAB Staff: Dr. Robert S. Shane, Staff Scientist, National Materials Advisory Board, National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington, D. C., 20418

LIAISON REPRESENTATIVES

Department of Defense:	Mr. Jerome Persh, Staff Specialist for Materials and Structures (Engineering Technology), ODDRE Department of Defense, Washington, D. C.. 20301
Department of the Army:	Mr. Bernard Reich - ECOM, Acting Chief, Solid State and Control Division, Code AMSEL-KL-S, U. S. Army Electronics Command Ft. Monmouth, New Jersey, 07703
Department of the Navy:	Dr. Paul N. Russell, Code 2020, Senior Technical Staff, Naval Electronics Laboratory Center, 271 Catalina Boulevard, San Diego, California, 92152
Department of the Air Force:	Mr. Maurice Chernoff, SAMSO/SYS (AFLC), Air Force Unit Post Office, Los Angeles, California, 92152
	Mr. Edward P. O'Connell, Rome Air Development Center (RCR), Griffiss AFB, New York, 13440
Advanced Research Project Agency:	Dr. Maurice J. Sinnott, Director Materials Sciences, Defense Advanced Research Project Agency Architect Building, 1400 Wilson Blvd., Arlington, Virginia, 22209

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Mr. Leon Hamiter, NASA - MSFC

Mr. Jules Wittebort, Air Force Materials Laboratory

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Dr. Robert S. Shane, Staff Scientist, National Materials Advisory Board was a continuous and valuable aid, contributor, stimulus, and catalyst.

The Panel wishes to express its sincere appreciation to all these people for their invaluable services.

William C. Hittinger, Chairman
National Materials Advisory Board
ad hoc Panel on Yield of Electronic
Materials and Devices

ABSTRACT

A study has been made of problems associated with production yield of electronic materials and associated devices. The fraction of starting material resulting in useful end-items is considered as the effective yield from the government's point of view. Reliability considerations are of necessity given important weight in the deliberations of the Committee. The report discusses practical problems of fabrication process and techniques, problems arising from current practice in specifications and standards, and problems arising from system applications and use. An unusual real-life case history of a major reliability study closes the report.

PREFACE

The National Materials Advisory Board of the Division of Engineering, National Research Council, National Academy of Science/National Academy of Engineering, was asked by the Department of Defense, Office of the Director, Research and Engineering, to initiate a specific sub-phase in the then-current study of the ad hoc Committee on Materials and Processes for Electron Devices. The sub-phase was to:

1. Identify the factors influencing production yield of electronic materials and related devices from the point of view of:
   a. Processing
   b. Fabrication
   c. Reliability and reproducibility
   d. Understanding of underlying phenomena
   e. Use

2. Consider alternative courses for solving the problems which were uncovered.

3. Recommend programs for which Government support would be effective.

4. Make such other recommendations as would be of benefit to the Government relating to production yield of electronic materials and related devices.

In November, 1970, the NMAB/NRC/NAS/NAE assembled an ad hoc Panel under the chairmanship of Mr. William C. Hittinger. He participated ex officio in the meetings and work of the parent NMAB ad hoc Committee on Materials and Processes for Electron Devices (Dr. Jack A. Morton, Chairman). The other Panel members did not attend the meetings of the Committee on Materials and Processes for Electron Devices nor did the Committee members attend the meetings of the Panel. However, the proceedings of each endeavor were freely available to the members of the other. No problem of communication existed.

The study was generally organized by first reviewing oral reports by the liaison representatives who presented the needs of the Services, their view of industrial problems, their current activities, their future plans, and relevant resource material. Thereafter, task forces were organized to develop specific studies and recommendations.

Three task forces were organized among the Panel members and liaison representatives. No distinctions were made during the working period. The Panel members, however, accept sole responsibility for the conclusions and recommendations of the study. The task forces and members were:

Task I - Fabrication

I. Arnold Lesk, Reporter

Martin M. Atalla

Morris Chang

Maurice Chernoff

Sohrab K. Ghandhi

Paul N. Russell

Task II - Specifications and Standards

Israel Katz, Reporter

Bernard Reich

Jerome J. Suran

Task III - System Application and Use

Max T. Weiss, Reporter

Maurice Chernoff

Charles Godwin

The organization of this Report is as follows:

Prefatory Material

Chapter 1 Introduction, Scope, Methodology

Chapter 2 Conclusions and Recommendations

Chapter 3 Fabrication Processes and Techniques

Chapter 4 Specifications and Standards

Chapter 5 System Application and Use

After the prefatory material, Chapter 1 covers introduction, scope, methodology, exclusions, criteria, and viewpoints. For the benefit of decision-makers and resource allocators, all the major conclusions and recommendations with an estimate of anticipated benefits are brought together in Chapter 2. The three task group presentations which give the background, discussion and greater detail for the conclusions and recommendations may be found in Chapters 3, 4, and 5. This report is closed by an unusual appendix which is a real life report of a major reliability study furnished through the courtesy of the General Electric Company.

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CHAPTER 1

1.0 INTRODUCTION

1.0.1 General Experience and Background

The U. S. semiconductor industry has grown to an annual level in excess of $1 billion for domestic and export sales during the approximately 20 years of its existence. This brief period has been paced by major advances in the ability to perform complex electronic functions at an ever-decreasing cost per function. In large measure the fundamental understanding of silicon and germanium material and device physics has reached a very high level of sophistication, which is adequate to support continued future growth in application to advanced products in all segments of the electronics industry.

Much remains to be done to improve overall cost effectiveness in applying these products to electronic systems. Both the component manufacturer and user have much to learn in dealing with the uniformity and reliability, specification, selection and application of the more than three billion units per year which are being produced at this time.

Many U. S. Government agencies feel that they are paying too much for their systems, or that the reliability of the systems they get is not adequate (See 1.0.2). In some cases, even after expenditures much larger than originally budgeted, an acceptable system was still not produced. There are examples of "trial-and-error" systems that eventually performed satisfactorily, but only as the result of expensive rework following unsuccessful first attempts. Although undoubtedly many factors contribute to such cases of budgetary and/or performance failure, the semiconductor component parts appear to bear some responsibility. On the other hand, there are examples of successfully developed systems. Some of these (Apollo, Minuteman III) are large "reliable component" systems, of such a nature that the consequences of a failure are enormous. Hence considerable sums of money were invested in programs to achieve sources of reliable components by which systems with predictable high reliability could be

designed and built. It may be argued that the cost per highly reliable system is large and, as a result, there is room to question whether or not reliability could have been obtained more economically by the "trial-and-error" technique. It is generally accepted that the "reliable component" approach is the only way that reliable systems can be built; there is much to recommend it for systems of all sizes. This is not to say that success is guaranteed by such an approach; some large systems that attempted a "reliable component" approach still got into difficulties because of problems with semiconductor components. In terms of our overall experience, then, the question addressed by this study may be restated as "How may we best capitalize on our collective knowledge to promote the design and production of semiconductor components for reliable, economical systems ?"

1.0.2 Department of Defense Inputs

Early in the deliberations of the Panel it became apparent that the liaison representatives shared a common view relating to the use of semiconductor devices in electronic equipment; namely, that the DoD Services are spending too much money for the value of their electronic equipment. They exemplified the situation in many ways:

- field maintenance of solid state electronic equipment is too expensive and difficult.
- reliability of solid-state electronic equipment is disappointing.
- semiconductor devices, integrated circuits in particular, are procured for use in military equipment in a wide variety of ways, often with little regard to end use.
- semiconductor devices, supplied for military end-use, often have latent manufacturing defects.
- there is little knowledge of differences in cost effectiveness between use of military standard and non-military standard parts.

The Panel concluded that there is a general problem in this field worthy of study, but no quantitative assessment of the problem was made. The members also concluded that they would have to carefully define and channel their activities since the questions raised by the liaison representatives had implications well beyond the purview and time available to the group.

The Charge to the Panel was to focus on "the yield of electronic materials and devices." The Panel chose to define yield very broadly as the ratio of usable silicon-based devices in a military system to the input of silicon at the front end of the manufacturing process. Silicon-based technology was focused on in depth as being generically applicable to electronic materials and devices. This approach was deemed most responsive to the interest of the sponsor.

It became readily apparent that the main liaison representative concerns were with matters usually considered as reliability-related: namely, the selection, specification and manner of use of a device for high system reliability, rather than the aspects of material, process, and structure associated with manufacturing yield, *per se*. The liaison representatives were concerned with device failure-related phenomena, but they viewed these matters as being the primary responsibility of the vendor. The Department of Defense has been a continuing and important sponsor of research and development of manufacturing methods in the solid state electronics field. Therefore, the Panel decided to examine in a balanced way all aspects of yield, defined above, relevant to present concerns about the expense of solid-state electronic systems.

1.1 SCOPE*

There are many electronic materials, processes, and devices of interest to DoD, but the problem stated by the liaison representatives: "DoD pays too much for what it gets," had such an immediate ring to it that the Panel decided to limit its considerations to silicon semiconductor device technology,

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* cf. 1.3 *infra*.

fabrication, test, specification, and use. The Panel also recognized that many yield-related considerations of other electronic materials were involved in the concurrent study* by the ad hoc Committee on Materials and Processes for Electron Devices, so that the focus on silicon devices was considered to be in order. This was particularly so since it was agreed that the generic nature of the silicon-based study would be capable of broad extrapolation and application.

In sum, the objectives of this study are to identify those problem areas from raw silicon to device use in military systems that adversely affect yield and to submit implementable recommendations for yield improvement.

1.2 METHODOLOGY

The Panel used a case-study approach. Real situations were described and investigated in both government and industry sectors. A number of Task Force members made visits to military contractors for direct observation and interview. Some, but not all, of the case studies are identified in this report. All were discussed by the Panel in the course of its deliberations.

1.3 OTHER CONSIDERATIONS AND EXCLUSIONS

In the course of the study, the Panel discussed certain management and policy questions but considered them inappropriate for implementation in specific recommendations. Worthy of mention in the context of the relationship between yield and reliability are the following:

Concern was expressed about the skill level required of military procurement personnel. A suggestion was made to classify the appraisal of the reliability aspect of procurement of devices as an R & D activity, thereby providing a means of upgrading this function.

The manufacture of semiconductor devices in offshore locations** was discussed extensively. Liaison representatives expressed concern about the use of such products in military equipment. Questions were raised about the ability to control integrity of manufacture in an offshore plant, the erosion of domestic manufacturing capability and related logistics problems in the event of war, and the

* Materials and Processes for Electron Devices. NMAB-289
** Offshore is used here to mean location in a foreign country.

possibility of sabotage in offshore factories. During the discussion the following points were made:

- There is a continuing world-wide trend toward assembly of semiconductor devices, particularly integrated circuits, in offshore plants. This is happening as a consequence of intense price competition in the industry.

- Reliability of semiconductor devices is unrelated to geographic location of manufacture. There are many examples of the ability to produce reliable products in well disciplined offshore plants. The determining criterion is the management ability to run a skilled factory; this ability is not necessarily geography-related.

- There are emerging trends in semiconductor fabrication toward design that can be assembled with minimum operator effort; e.g., beam lead and "bump" connections. Success in these areas could minimize the need for offshore assembly in the future.

The government must recognize the need to pay appropriately for domestically manufactured products where it is deemed essential to procure such devices. There must not be an exclusive insistence on lowest first price in such procurements; but, rather, a balanced view of all elements of system cost should prevail.

A question was raised about the need or desirability of the government undertaking its own manufacture of semiconductor devices in an arsenal complex as a means of retaining domestic source of supply and obtaining required high reliability levels. The Panel felt that taking advantage of the large volume manufacture of U. S. industry is the best means for low device cost and high reliability, and that what is required is to learn best how to control such manufacture and specify and procure for military requirements.

No attempt has been made to identify deficient contractors or agencies in this report, although a high level of frank interchange occurred in deliberations. Rather, effort was made to identify generic problems and solutions with appropriate recommendations.

Conclusions and Recommendations are summarized in Chapter 2; they are contained in greater detail in Chapters 3 through 5.

CHAPTER 2

2.0 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

Since we are dealing with a mature technology, the reader will understand that it is necessary to make many specific recommendations as well as a few broadly based recommendations for major change. The Panel's main conclusions, recommendations and anticipated benefits are summarized in this Chapter. First they are grouped into three categories of task force studies:

- Fabrication Processes and Techniques
- Specifications and Standards
- System Application and Use

Following this they are ordered by priority, thereby signifying the best judgment of the Panel as to relative importance. The reader is referred to the appropriate chapter for more detailed discussion of each point.

2.1 FABRICATION PROCESSES AND TECHNIQUES

2.1.1 Crystal Defects

2.1.1.1 Conclusion

Crystal lattice defects can result in yield losses in such large area devices as power transistors (low and high frequency), thyristors, and complex integrated circuits. The role of defects in reducing yield and the means by which they may be introduced during crystal growth and in the manufacturing process are not well understood.

2.1.1.2 Recommendation

A program should be supported to elucidate the fundamental processes by which crystal defects are initiated, and by which they move and multiply in a silicon wafer during processing. This program should aim at determining the mechanisms by which these defects are created during processing, and should aid in the formulation of low defect processing procedures.

2.1.1.3 Anticipated Benefits

Higher device yields with possibly greater device uniformity, leading to more tightly controlled device parameters, may be expected. This in turn, should directly improve the margin of tolerance which can be allowed in circuit designs, and lead to the design of more reliable circuits.

2.1.2 Metallization

2.1.2.1 Conclusion

The problem of metallization of conductor paths in integrated circuits is a major contributor to decreased yield and poor reliability. This is especially true when the conductors are subject to thermal cycling, high peak current pulses, or to low level corrosion. This problem is greatly exacerbated when conductors are deposited over large steps on the oxide surface and when they contact very shallow p-n junctions. In particular, the problem of metallization has slowed progress in complex large scale integration, where two or more metallization layers are desirable.

2.1.2.2 Recommendations

A program should be instituted which:

- Aims at discovery of the fundamental failure modes that are presented in various metal systems, under a variety of stressful conditions, e.g., high current density, large steps in the oxide, temperature-power-current cycling, etc.
- Aims at development of quantitatively controllable procedures by which the risk level in these failure modes can be minimized.
- Undertakes to transfer these procedures to actual manufacturing practices with the assurance that benefits of this work will be ongoing.

2.1.2.3 Anticipated Benefits

This program should lead to enhanced reliability and more effective reliability assurance, thereby giving higher yields of large-scale integrated circuits.

2.1.3 Bonding

2.1.3.1 Conclusion

Both die and wire bonds are primary areas for failure of semiconductor devices and integrated circuits. It is expected that the chip size as well as the number of terminal pads will increase in the future, due to the need for increasingly complex large-scale integrated circuits. Hence these problem areas can be expected to become more serious in the future.

2.1.3.2 Recommendations

A program should be developed to:

- Achieve quantitative basic understanding of what occurs when die and wire bonding are performed.
- Explore new metallurgical systems for these functions.
- Explore new bonding systems that will increase process control now seemingly inherently deficient in bonding processes.
- Develop methods for evaluating the quality of bonds, preferably in a non-destructive manner.

2.1.3.3 Anticipated Benefits

Enhanced reliability and more effective reliability assurance may be anticipated with beneficial impact on cost-effectiveness.

2.1.4 Plastic Encapsulation

2.1.4.1 Conclusion

Economic pressures are leading to a growing use of plastic encapsulated semiconductor components, in particular, integrated circuits. These devices are providing adequate service in a variety of nonmilitary products. They have been

excluded from most military systems because of concern for their ability to meet stringent environmental conditions. There is a considerable variability in the behavior of these devices under high stress; this is a reflection of the poor understanding of polymeric materials and their processing for this application.

2.1.4.2 Recommendations

A program should be established to:

- Study the various classes of macromolecular encapsulants.
- Study the basic mechanisms by which these are polymerized during encapsulation.
- Study their basic properties, which relate to reliable microcircuit encapsulation. This part of the program should be directed at development of means for precisely specifying the formulations for these encapsulants so they may be well controlled and their proper use in the molding operation strictly delineated.
- In addition, the study should focus attention on inspection screens for plastic encapsulated semiconductor components, since these are not now fully effective in establishing quality assurance.

2.1.4.3 Anticipated Benefits

Plastic packaging is an important approach for reducing costs of components. This cost saving could be applied to appropriate government systems provided adequate reliability and quality assurance are demonstrated.

2.1.5 Hermetic Packaging

2.1.5.1 Conclusion

At the present time hermetic encapsulation is used for most military transistors and microcircuits. The reliability of this form of packaging is affected by many factors: contamination that is present within the package before lidding, sealing contamination, and subsequent contamination due to voids in improperly formed seals. All of these forms of contamination can result in long-term failure.

2.1.5.2 Recommendation

A program should be instituted to characterize the detailed nature of the seal on hermetic packages, to evolve better hermeticity tests, and to develop techniques by which large-area seals can be formed with assurance of integrity. Better techniques for detecting and eliminating contaminants that get sealed within the package should be part of this program. In addition, new ways of sealing the microcircuit at the chip level should be investigated, with a view toward reducing the effects of contamination and improper hermetic encapsulation.

2.1.5.3 Anticipated Benefits

Enhanced reliability and more effective reliability assurance may be expected.

2.1.6 Reliability Assurance

2.1.6.1 Conclusion

The effectiveness of reliability assurance procedures is limited by the degree of our understanding of failure mechanisms. Relatively little research and development effort directly applied to Physics of Failure has been sponsored (although the fine work of the Air Force's Rome Air Development Center, among others, is recognized).

2.1.6.2 Recommendations

Sponsor programs to:

- Establish more meaningful and economical screens that are materials/process oriented rather than component oriented.
- Evolve pertinent high-stress (destructive) tests for faster and more accurate reliability prediction.
- Perform research and development in physics of failure relating to the dominant failure modes.
- Study new techniques for more effective production control of materials and processes.
- Evolve effective techniques for the economical reliability assurance of low-volume parts.

2.1.6.3 Anticipated Benefits

A more quantitative understanding of failure mechanisms pertinent to semiconductor components, leading to better screens and more meaningful interpretation of destructive tests would be achieved. Effective screens for low-volume parts would be developed.

2.1.7 Procurement

2.1.7.1 Conclusion

Procurement practices contribute in a major way to the problems encountered by the government in obtaining high-yield, reliable, economical systems. Modernization of procurement procedures should be done periodically. Although effective procurement procedures have been established by the military agencies and NASA, there is a need for consolidation and integration. In many cases established procurement procedures are not practiced.

2.1.7.2 Recommendations

- Sponsor a program to compile a listing of the various agencies, documents, procedures, and reports relating to the procurement of high-reliability semiconductor components.
- Study the economics of high-reliability ("hi-rel") component procurement as they relate to system cost and performance to ascertain what first cost for components would make economic sense.
- Report on the practices of competitive bidding as they affect the ability of the system manufacturer to use the best techniques for "hi-rel" assurance.
- Study the economic problems of line certification as they relate to volume of production.
- Recommend ways in which production control may be more effectively implemented and documented.
- Perform and publish failure analysis related to specific production processes for use in follow-on procurement.

2.1.7.3 Anticipated Benefits

This Panel anticipates that a better understanding of the semiconductor device procurement system and how it works, will be achieved, leading to an improved, integrated procurement system for all government agencies with benefits of economy, reliability, and scheduling.

2.1.8 Government Agency-Industry Committee

2.1.8.1 Conclusion

Various government agencies, professional societies and semiconductor-component suppliers are working together to establish high-reliability (hi-rel) procedures for semiconductor components. However, there is a lack of coordination, duplication of effort, and self-centered motivation.

2.1.8.2 Recommendation

A government-industry committee should be constituted to implement mobilization of the hi-rel practices used today, extract meaningful data from past and present hi-rel programs, assist in standardization of documents, and promote the exchange and dissemination of pertinent information.

2.1.8.3 Anticipated Benefits

Establishment of a single government-industry committee to coordinate semiconductor component hi-rel activities should lead to improved economy and effectiveness of hi-rel procedures.

2.2 SPECIFICATIONS AND STANDARDS

2.2.1 Specification Rigidity

2.2.1.1 Conclusion

Military (MIL) specifications are too rigid. Furthermore, they do not keep up with the state of the art. In particular, they currently are not sufficiently specific to end-applications. One useful approach might be to modify them for classes of service.

2.2.1.2 Recommendations

- The scope of specifications should be limited by class of service.
- An effort should be made to supply specification formats that would help the specification writer. These formats should be living documents subject to planned periodic

change by a group of competent individuals with adequate device experience and laboratory backup, assigned to specification research and development.

- The flexibility of military specifications should be increased by limiting their use in logistic documentation and by preparing and using them primarily for new equipment applications.

- For those components fabricated by high-volume production, there should be government leadership in the area of device specification because no single industrial contractor is in a position to exert the broad leadership required.

2.2.1.3 Anticipated Benefits

Use benefits should more closely match dollars spent for procurement.

2.2.2 Application and Use

2.2.2.1 Conclusion

There are many factors influencing device reliability (and, hence, apparent yield) which are related not only to fabrication but also to subsequent integration and use in subsystems and systems operating in a field environment.

2.2.2.2 Recommendations

Competent support under one organization must be supplied to assure that no interface problems arise concerning the application of devices to circuits and from circuits to higher levels of integration. Standard procedures must be developed to guarantee the smooth integration of these parts.

A practical system must be developed whereby feedback, obtained from the equipment developers and users, is made available to the device designer so that deficiencies in device design and fabrication can be identified and corrected.

2.2.2.3 Anticipated Benefits

Redesign as a result of field failure experience will be minimized. Design improvement as a result of experience will be accelerated. In our concept of yield a marked improvement may be expected.

2.2.3 Commercial Practices

2.2.3.1 Conclusion

Experience has shown that well-managed use of high-volume-produced, commercially available semiconductor devices in military equipment can provide performance and reliability equal to that of counterpart military standard devices. Moreover, data accumulated on system reliability show that not only does the production of complex electronic equipments pass through a shakedown phase before desired reliability is achieved, but also that non-military standard devices have performance and reliability characteristics after production shakedown that qualify them for applications in military equipments.

Although the use of non-military standard devices in the production and maintenance of military equipment is not without risk, significant cost reduction and system reliability improvements may be attainable.

2.2.3.2 Recommendation

The government should undertake a program to determine whether high-volume-produced, non-military standard, commercially available devices, particularly large-scale integrated circuits could be utilized in different generic classes of equipment, in a truly cost-effective manner, where cost-effectiveness is measured over the life cycle of the equipment.

2.2.3.3 Anticipated Benefits

Large cost savings may be realized if acceptable commercial practices as well as non-military standard, commercially available devices were used in the production of large-quantity military equipment.

2.2.4 Equipment-Reliability Enhancement

2.2.4.1 Conclusion

Reliability enhancement, device or equipment standardization, and systems failure analyses, as currently practiced, are often assigned to the manufacturing phase of the equipment-procurement process. Consequently, they may not receive adequate attention from persons with appropriate levels of technical competence. Moreover, sufficient design effort to improve levels of device, equipment and system performance or to reduce equipment downtime, thereby greatly extending system operating life between overhauls, is seldom part of a procurement contract. Yet, a significant increase in the field life of equipment between overhauls should be an attainable goal.

Equipment-procurement costs are easily identifiable and in most instances readily determinable. Reliability assessment is more difficult to perform. Fund allocations for reliability enhancement often are not given appropriate consideration and priority.

2.2.4.2 Recommendation

The history of the reliability and the actual life of existing equipment should be a decisive factor, in combination with original price, for selection and procurement of subsequent devices and equipment. To obtain such data in order to apply experience to the design and production of new equipment will require specific funding for reliability improvement in procurement contracts. Therefore, reliability enhancement should become a procurement requirement.

2.2.4.3 Anticipated Benefits

A useful criterion for bid evaluation will be achieved. An incentive for ongoing product improvement will be incorporated in the systems. Net mission cost should be reduced.

2.2.5 Screening and Burn-In

2.2.5.1 Conclusion

Screening and burn-in at both the device and subsystem levels have been useful in detecting nonconformance and early failure. The DoD position relative to general application of screening and burn-in is not clear. If the techniques are effective in lessening early failures, then they should be made mandatory for all components and subsystems procured by DoD.

At present, the sequence of screening and burn-in is a fixed pattern of tests for all detail specifications based on test methods in MIL-STD-750 and MIL-STD-883.

2.2.5.2 Recommendations

Device and subsystem screening and burn-in should be studied as techniques for enhancing system reliability and cost effectiveness. Recognition should be given to the need for greater flexibility in applying the preconditioning and burn-in sequence according to class of service.

2.2.5.3 Anticipated Benefits

Higher yield through greater reliability of screened components should be attained.

2.3 SYSTEM APPLICATION AND USE

2.3.1 Conclusion

Development and procurement procedures for highly sophisticated and critical DoD weapons systems often result in less than satisfactory field performance because of high component-failure rates, particularly in integrated circuits. Though the initial cost of the integrated circuits may seem to be reasonable, the impact on cost, schedule and operational readiness of failures

at higher levels of assembly, or of field failures, leads to the conclusion that improved techniques must be devised to ensure dependable high reliability at the component level. This is particularly true for mission critical aircraft and space and missile systems.

Although the previous recommendations would clearly improve this situation, the Panel recognizes that some major critical national programs have developed effective techniques for the utilization of electronic components that ensure a very high level of dependability and reliability. These techniques involve focusing management, engineering, and fiscal attention on reliability as a main goal, a condition that has been difficult to apply to the broad spectrum of military systems.

It is clear that not all programs can be elevated in importance to command the funding and sustained effort in the component-acquisition program that is put into the few exceptional programs; the following question still arises: "Can DoD as a whole use its immense resources and purchasing power to achieve a very high level of reliability (and thereby, improve yield) for all its mission critical aircraft and space and missile programs? Can it do this by cost-sharing among programs without burdening each individual program with excessive costs?"

This concept of total component management is viewed as the overall means by which various of the preceding procurement recommendations, recognition of classes of service (2.2.1) and use of certain commercial practices (2.2.3), in particular, can best be judged in total perspective. The Panel believes that a study in greater depth than was possible in this effort should be undertaken to evaluate the long-range implications of the total management concept. A suggested course of action based on the considerations of Chapter 5 (q. v) are set forth below.

2.3.2 Recommendations

- Establish a committee of highly qualified and experienced individuals both in and out of government. These individuals should have backgrounds in both the technical and

management areas of DoD systems in order to study the advisability and practicality of establishing a single DoD agency with responsibility and authority for consolidating the management, procurement, and technical surveillance of high-reliability components for military applications. This agency should concern itself with all devices, whether procured by the government or by its contractor for high-reliability military systems.

This committee should also address itself to the problems of developing programs and techniques for ensuring a continuing advancement in reliable component technology, with emphasis on integrated circuits. This advancement might otherwise be stifled by the constraints to use specific approved types such as those that a single-agency procurement system might impose.

2.3.3 Anticipated Benefits

The vast purchasing power of DoD could be used to improve component yield, reliability, and, thereby, overall system cost. Further, the considerable benefits potentially available from current experience in methods developed in obtaining high reliability in mission-critical programs such as Apollo and some missile and space programs could be exploited in many DoD programs.

2.4 PRIORITY ORDERING OF RECOMMENDATIONS

The recommendations made in the preceding paragraphs are ordered in priority in the following table according to criteria related to the broad question of electronic equipment cost effectiveness. The Panel regrouped its recommendations, listed previously by Task Force category into categories of Fabrication, Reliability, and Reliability Assurance, and Specifications and Procurement. In so doing it was

decided that each category has approximately equal importance in relation to yield as defined for this study. The priorities assigned in the following table, therefore, apply only within the category. No attempt was made to weight the ratings from category to category. Priorities are assigned from A through D in descending order of importance to DoD.

Table - Priority Ordering of Recommendations

	Recommendation Number (s)	Priority
Fabrication		
Crystal Defects	2.1.1	C
Metallization	2.1.2	A
Bonding	2.1.3	A
Plastic Encapsulation	2.1.4	A
Hermetic Packaging	2.1.5	A
Production Control	2.1 - 2.5 Inclusive 2.1.6 (. - #4)	A
Reliability and Reliability Assurance		
Nondestructive Testing	2.1.6 (. - #1)	A
High-Stress Destructive Testing	2.1.6 (. - #2)	B
Physics of Failure	2.1.6 (. - #3)	B
Screening and Burn-in	2.1.6 (. - #5), 2.2.5	B
Specifications and Procurement		
Military Specifications	2.2.1	B
Application and Feedback	2.2.2	A
High-Volume, Non-Standard	2.2.3	D
Reliability Enhancement	2.2.4	B
Component Procurement and Control (at individual and system level)	2.1.7, 2.1.8, 2.3 (. - #1 & #2)	A

CHAPTER 3

3.0 FABRICATION PROCESSES AND TECHNIQUES

3.1 OBJECTIVES

The specific objectives of this Chapter on Fabrication Processes and Techniques are to identify those aspects of semiconductor component manufacture that constitute problem areas incorporated in the statement of overall Panel objectives and to relate its findings to those of the other Chapters of this Report.

3.2 MANUFACTURING CONSIDERATIONS

3.2.1 Device Fabrication

The dramatic decrease in cost per function of semiconductor devices over the years has been paced by the cost reduction impact of fundamental understanding of materials, processes, structures and production techniques. Future emphasis will shift away from basic materials and structures to manufacturing control, testing, and quality and reliability assurance.

Some important material-structure challenges worthy of fundamental investigation remain, particularly as they relate to more complex devices with advanced performance which are being developed. Recommendations are made in Section 3.3.1 for the following categories:

- crystal defects.
- metallization
- bonding.
- plastic encapsulation.
- hermetic packaging.

3.2.2. Cost

The selling price of semiconductor components for consumer/industrial application has continuously dropped during the past fifteen years to the point where prices are so low that several major companies have gone out of the semiconductor business for lack of profit. Most devices and integrated circuits

sell for less than a dollar, many for a few cents. Hence, it cannot be argued that semiconductor components are too expensive. In addition, general reliability has proven to be very high based on experience data over a period of many years. Quality problems have generally been worked out between supplier and user, frequently resulting in improved components and end products. Replacement of semiconductor devices in consumer/industrial products is relatively easy. However, for high reliability (hi-rel) application, there is the added requirement of proof of reliability before use. This is where the additional (and appreciable) cost of hi-rel components originates.

The large price differential between consumer/industrial and hi-rel parts provides a temptation for equipment manufacturers to use the cheaper units. A more difficult problem is the construction of equipment that does not perform reliably even though hi-rel parts are used; in other words, some hi-rel components are not sufficiently reliable, or failures have occurred because of poor application. Both reliability procedures and procurement procedures contribute to the problem. These are discussed in the following sections; conclusions are based on information obtained from the bibliography (3.4) and from the experience available to the Panel.

3.2.3 Reliability Procedures

Various procedures have evolved with the objectives of: (a) determining the reliability of a particular semiconductor component, (b) removing the least reliable units from a production distribution, and (c) maintaining production of a given device at a consistent level of reliability. How well these procedures work, and which are the most useful, are subjects of considerable debate. However, the procedures are essential to the procurement of hi-rel components and, through the application of advancements in reliability physics, they are continually improving.

3.2.3.1 Screening

Screening (100% nondestructive testing) is the process of subjecting all units of a given production type to a prescribed series of tests, the objective of which is to weed out the components that are malfunctioning or have a high probability of exhibiting unacceptably low reliability. It is the most commonly used

technique for reliability enhancement. Screening is performed by the manufacturer, by the user, or both. When performed by the user, screening serves as an incoming inspection to help reduce the impact of a manufacturer's mistakes or to economize on that part of a manufacturer's testing costs if he is relieved of screening responsibility.

The following observations can be made based on experience with screening of semiconductor components.

1. System reliability is higher using screened rather than non-screened parts (i.e., hi-rel parts are more reliable than commercial/industrial components).

2. In general it is cheaper to employ initial screens rather than utilize non-screened components and then perform equipment fixes. Equipment procurement costs can be identified, but costs of reliability "retrofit" can be unattainable.

3. Parts cost is about 10% of the first cost of a system Screening can add appreciably to component costs, but not significantly to a system's first cost.

4. Some screening tests are common to all components, others may be unique to a particular device or integrated circuit. Screening approaches used on discrete devices may not apply to integrated circuits.

5. There may be differences in the results of suppliers and users running the same screens.

6. There are cases where serious doubt exists that the manufacturer performed all required screening tests due to incomplete lot history data.

7. For most effective use of screening procedures, there must be close customer-vendor interaction and information feedback.

8. If screening requirements are too rigorous, many good units will be discarded resulting in low yield and high cost.

9. A particular screening procedure may be non-destructive for some components, and may be destructive or detrimental to the reliability of others.

10. Some failure modes are screened by standard techniques; other failure modes are only occasionally detected.

11. Advanced techniques (e.g., scanning electron microscope inspection) are being applied to screening. They must be properly applied for effectiveness and economy.

3.2.3.2 High-Reliability Considerations

For highest reliability, screening (100% nondestructive testing) is not sufficient. As is commonly stated, "high reliability must be designed in, not tested in." The simple reason for this is that we know how to screen for some failure modes but not for others. Certainly, as the field of reliability physics advances, we learn more about failure mechanisms which allows the establishment of more effective screens. However, the time when screening alone will serve to eliminate all potential failures will probably never come.

The basic concept for high-reliability assurance consists of 100% screening plus sample destructive testing of each production lot. All failures are analyzed for failure mode, and grouped. A lot is accepted or rejected on the basis of either the number of failures, or the character of the failures; i.e., whether they are screenable as opposed to non-screenable (insidious and long-time dependent).

Lessons learned from high reliability efforts leads to the following list (not necessarily complete):

1. Proper failure analysis and reporting are an essential aspect of the high reliability procedure.
2. Failure mode analysis of integrated circuits is complicated by the fact that not all component elements are accessible.
3. A positive attitude of the supplier towards hi-rel production is important. His personnel must be properly trained and motivated.
4. Volume procurement is necessary for the establishment of proved low failure rates.
5. System reliability may be enhanced by reducing the number of different parts in the system and using parts fabricated by a common technology.

3.2.3.3 Production Control; Line Certification; Captive Line

The high-reliability procedure (3.2.3.2) requires for its practical implementation the knowledge that a production line can be controlled to turn out a consistent product. Realizing that production control is the foundation upon which all reliability assurance techniques must rest, large users of semiconductor components for hi-rel systems have generally established two procedures for guaranteeing production control on the lines that manufacture their products: line certification and the captive line.

1. Line certification requires that the manufacturer meet specific standards of control and documentation on his line, and that the product pass prescribed screening tests. The certification process is a continual one to guarantee that a line, once under control, remains that way or loses its certification.

2. The captive line is a production line on the supplier's premises that is under control of the user. The user may specify completely the materials, processes, equipment, procedures, documentation and tests, and inspect the line for compliance.

Some observations can be made from experience with these specialized production lines:

(1) Critical production steps must be kept constant, but the system must allow for modification to incorporate improvements.

(2) Yield and reliability problems must be differentiated. Sometimes they are related, sometimes not.

(3) Line certification requirements must be effective and economical. Over-control can create considerable expense.

(4) Line certification requirements should accommodate different steps by different manufacturers.

(5) Line certification requires periodic renewal.

(6) Government agency personnel at the manufacturer's location serving as resident inspectors must be highly qualified. Often they are not.

3.2.3.4 Standard Parts, Preferred Parts, and Non-Standard Parts

The high reliability procedure (Section 3.2.3.2) is an effective way to obtain reliability assurance for the semiconductor component complement of a large system. It is also expensive, and would be prohibitively so if applied to a small system.

A related system has the objective of obtaining standard reliabile parts for general use.

A standard part is one that passes the appropriate set of military specification tests (MIL-M-38510 for integrated circuits, MIL-S-19500 for discrete devices), which include screening. A discrete device must also have an EIA registration. Methods of test for qualification are specified in MIL-STD-833 (integrated circuits) and MIL-STD-750 (discrete devices).

There is also a list of preferred discrete devices (published in MIL-STD-701) determined by a committee with members representing the armed services and users. A semiconductor component appearing on this listing, which is updated periodically, may be required for a hi-rel system.

In cases where an equipment manufacturer wants to use a component that is neither "standard" nor "preferred," he may request that it be approved and must supply supporting data. Methods of approval for the use of non-standard parts are listed in MIL-STD-749B.

Additional observations include:

(1) Test methods and procedures do not exist for newer items (e.g., Metal-Oxide Semiconductors (MOS), Large Scale Integrated Circuits (LSI)).

(2) A non-standard part is used either by testing the lot to a procurement specification together with the issuance by the producer of a certificate of compliance, or by a waiver of the specification requirements.

(3) A non-standard part may be a standard part changed slightly so the manufacturer will not have to perform some of the tests required for the standard part.

3.2.3.5 Failure Analysis and Documentation

The key to any successful program in reliability is detailed failure analysis with satisfactory documentation.

(1) In general, documentation of failure has been incomplete, failure analysis is incomplete, and information fragmented or missing. Up to now, the best documentation has been done by NASA.

(2) Each failure should be related to a responsible manufacturing process where applicable.

(3) Failures may be induced in many ways, such as overstress in testing, mechanical mishandling and misapplication (e.g., noise pulses in a system power supply). They may also be inherent in the component.

(4) Realistic documentation of failures may be hindered by company proprietary considerations.

(5) Reliability problems with the highest frequency occur prior to equipment reaching operational status.

3.2.4 Procurement Procedures

Procurement procedures can contribute to problems in system reliability in various ways. In many cases, after a problem has been identified, it can be concluded that if procurement had proceeded as it should have, the problem would not have occurred. The usual reason for procurement procedural relaxation is schedule constraint. This leads many people to ask the old question: "Why is there never time to do it right, but always time to do it over?"

This Panel notes certain procurement practices:

(1) Because of time and/or monetary problems, specification requirements are often waived.

(2) Prime contractors do not, but should, include the cost of assuring that suppliers comply with all quality requirements of the prime contract in their budget or cost estimates.

(3) Competitive bidding to obtain systems contracts may force bidders to relax reliability requirements to cut costs in order to get the business.

(4) Competitive bidding for components by systems contractors tempts component manufacturers to shortcut screening tests to reduce costs.

(5) Vendor-to-vendor interchangeability is often nonexistent.

(6) Since offshore labor is less expensive, decisions as to the amount of control to be implemented are made relative to different cost factors. Extra control can be more cost-effective offshore than in the U. S.

(7) Established procurement procedures are not followed in many cases.

3.3 STUDY TOPICS

The following topics should form the subjects of sponsored programs to satisfy the objectives of this study.

3.3.1 Specific Research Programs

The following areas would be most fruitful in improving yield and should be the subjects of specific programs aimed at understanding and control in a production environment.

3.3.1.1 Crystal Defects

3.3.1.1.1 Conclusions

In general, there exists an adequate supply of sufficiently pure silicon for the domestic manufacture of transistors and microcircuits in the United States.

Crystal lattice defects can result in yield losses in such large area devices as power transistors (low and high frequency), thyristors, and complex integrated circuits. The role of crystal defects in reducing yield and means by which they can be introduced during crystal growth and in the manufacturing process is not well understood.

3.3.1.1.2 Recommendation

Support a program to determine the fundamental processes by which crystal defects are initiated, and by which they move and multiply in a silicon wafer during processing. This program should aim for the formulation of low defect processing procedures.

3.3.1.1.3 Anticipated Benefits

This program should lead to higher device yields with possibly greater device uniformity, thereby permitting more tightly controlled device parameters. This, in turn, should directly improve the margin of tolerance which can be allowed in circuit designs, and lead to the design of more reliable circuits.

3.3.1.2 Metallization

3.3.1.2.1 Conclusion

Defects in metallized conductor paths in integrated circuits are a significant contributor to decreased yield and poor reliability. This is especially true when the conductors are subject to thermal cycling, high peak current pulses, or to low level corrosion. This problem is greatly exacerbated when conductors are deposited over large steps on the insulator surface, and when they contact very shallow p-n junctions. In particular, problems of metallization have slowed progress in complex large scale integration, where two or more metal layers are highly desirable.

3.3.1.2.2 Recommendation

A program should be instituted which:

- Identifies the fundamental failure modes that are present in various metal systems, for a variety of high stress conditions, e.g., high current density, large steps in the underlying or overlaying dielectric insulator, temperature-power-current cycling, etc.
- Develops quantitatively controllable procedures by which the risk of these failure modes can be minimized.
- Transfers these procedures to actual manufacturing practices with the assurance that benefits of this work will be achieved in an ongoing manner.

3.3.1.2.3 Anticipated Benefits

It would be expected that there would ensue enhanced reliability and more effective reliability assurance as well as higher yield or large scale integrated circuits.

3.3.1.3 Bonding

3.3.1.3.1 Conclusion

Both die and wire bonds are primary areas for failure of semiconductor devices and integrated circuits.* We expect that both the chip size as well as the number of terminal pads will increase in the future, due to the increasing need for complex large scale integrated circuits. Hence these problem areas can be expected to become more serious.

3.3.1.3.2 Recommendation

A program should be developed to:

- Study the basic mechanisms for quantitative understanding of die and wire bonding.

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* cf. National Bureau of Standards Technical News Bulletin, October, 1971, pp. 248 ff, for an excellent brief, but thorough, discussion.

- Explore new metallurgical systems for these functions.
- Explore new bonding systems which will eliminate or reduce the lack of control now inherent in present systems.
- Develop methods for evaluating the quality of bonds, preferably in a non-destructive manner.

3.3.1.3.3 Anticipated Benefits

Enhanced reliability and more effective reliability assurance would be anticipated.

3.3.1.4 Plastic Encapsulation

3.3.1.4.1 Conclusion

Economic pressures are leading to a growing use of plastic encapsulated semiconductor components, integrated circuits in particular. Plastic encapsulated consumer and industrial devices have proven performance records. The same can be said for their usage in military fuzes. It is economically desirable that plastic encapsulation be incorporated more generally into military systems. Unfortunately, polymers for this application are poorly characterized and specified. There is consequently, considerable variation in available polymeric products and in their processing techniques. Thus, they exhibit variable reliability performance under military environments.

3.3.1.4.2 Recommendation

A program should be funded to study the various classes of plastic encapsulants, the basic mechanisms by which these are polymerized during encapsulation, and their basic properties which relate to reliable encapsulation. Valuable results of this program would be the development of precise means for specifying the formulation for these encapsulants and the details of the encapsulation process so that highly predictable results could be obtained. In addition, the study

should focus attention on appropriate testing screens for plastic encapsulated semiconductor components.

3.3.1.4.3 Anticipated Benefits

The plastic package promises to be an important approach for reducing costs of components. This cost saving can be applied to government systems provided adequate reliability and quality assurance can be demonstrated.

3.3.1.5 Hermetic Packaging

3.3.1.5.1 Conclusion

Presently hermetic encapsulation is used for most military transistors and microcircuits - the primary exception being in weapon fuzes where plastic encapsulated parts are used almost exclusively. The reliability of hermetic packaging is a function of many factors:

Contamination that is present within the package before lidding (organic matter, metallic particles, etc.).

Sealing contamination (such as solder balls which fall into the package due to an excess of solder during the sealing operation.

Contamination entering through voids in improperly formed seals.

All of these forms of contamination can result in long term failure.

3.3.1.5.2 Recommendation

A program should be instituted to characterize the seal on the hermetic package, to evolve better hermeticity tests, and to develop techniques by which large area seals can be formed with integrity. Better techniques for detecting and eliminating contaminants that get sealed within the package should be an objective of this program. In addition, new ways of sealing the microcircuit at the chip level should be investigated, with a view towards reducing the effects of contamination and improper hermetic encapsulation.

3.3.1.5.3 Anticipated Benefit

Enhanced reliability and more effective reliability assurance would be anticipated.

3.3.2 Procurement

3.3.2.1 Conclusions

Procurement practices contribute in a major way to the problems encountered by the U. S. Government in obtaining reliable, economical systems (3.2.4). Modernization of procurement procedures should be done.

3.3.2.2 Recommendations

- Sponsor a program to compile a listing of the various agencies, documents, procedures, and reports relating to the procurement of high reliability semiconductor components.
- Study and report the economics of hi-rel component procurement as it relates to system cost and performance to ascertain what first cost for components would make economic sense.
- Report on the practices of competitive bidding as they affect the ability of the system manufacturer to use the best techniques for hi-rel assurance.
- Study the economic problems of line certification as they relate to volume of production.
- Recommend ways in which production control may be more effectively implemented and documented.
- Study the relation of failure analysis to specific production processes.

3.3.2.3 Anticipated Benefits

A better understanding of the semiconductor procurement system and how it works should be achieved. This should lead to a basis for developing an improved, integrated procurement system for all government agencies with benefits of economy, reliability and scheduling.

3.3.3 Reliability Assurance

3.3.3.1 Conclusions

The effectiveness of reliability assurance procedures is limited by the degree of our understanding of failure mechanisms. Relatively little R & D effort directly applied to physics of failure has been sponsored. Further effort is required to advance knowledge in the fields discussed under 3.2.3 Reliability Procedures.

3.3.3.2 Recommendations

- Sponsor programs to establish more meaningful and economical screens (nondestructive evaluation) which are materials/process oriented rather than component oriented.
- Evolve pertinent high stress (destructive) tests for faster and more accurate reliability prediction.
- Perform R & D in Physics of Failure relating to the dominant failure modes.
- Study new techniques for more effective production control of materials and processes.
- Evolve effective techniques for the economical reliability assurance of low volume parts.

3.3.3.3 Anticipated Benefits

A more quantitative understanding of failure mechanisms pertinent to semiconductor components would lead to better screens, more meaningful interpretation of destructive tests, and effective screens for low volume parts.

3.4 GOVERNMENT-INDUSTRY COMMITTEE ON HIGH-RELIABILITY PROCEDURES

3.4.1 Conclusions

Various government agencies, professional societies and semiconductor component suppliers are working together to establish hi-rel procedures for semiconductor components. However, there is duplication of effort, lack of coordination and self-centered motivation.

3.4.2 Recommendations

- Study the various national and international contributions to hi-rel procedures.
- Institute a government-industry committee which will extract meaningful data from past and present hi-rel programs; assist in standardization; promote the exchange and dissemination of information; and implement mobliza- tion of the hi-rel practices used today.

3.4.3 Anticipated Benefits

Establishment of a single government-industry committee to co-ordinate semiconductor component hi-rel activities on national and international bases will lead to improved economy and effectiveness of hi-rel procedures.

3.5 RECOMMENDED READING

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19. Military Specification - Semiconductor Devices. MIL-S-19500.

20. Military Standard - Test Methods and Procedures for Semiconductor Devices. MIL-STD-750.

21. Non-Standard Parts Approval System, MIL-STD-749.

22. Preferred Parts Listing, MIL-STD-701.

23. NASA-SP-287.

24. Reliability Considerations in Plastic Encapsulated Microcircuits, Technical Monograph 71-1. Reliability Analysis Center, Rome Air Development Center Research and Technology Division, Air Force Systems Command, Griffis Air Force Base, N. Y., 13440, December 1971.

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CHAPTER 4

4.0 SPECIFICATIONS AND STANDARDS

4.1 INTRODUCTION

The semiconductor industry has generated an almost unlimited variety of device types, covering a wide spectrum of electrical and mechanical characteristics and a multiplicity of application ambients. As a consequence it has been exceedingly difficult to maintain any semblance of standardization and selection for optimum cost-effectiveness in military applications.

The strong interactions between the method of specification and procurement and device performance yield, and cost make the problem of particular importance. As integrated circuit complexity increases, the interrelationship between yield of component and specification becomes of even greater significance.

The Panel identified a number of needs for improvement in the military specification and procurement function. There are numerous instances today in which the procurement procedure either is so deficient as to allow for the use of improper devices in critical systems or is so restrictive as to inhibit the cost effectiveness of the system. A number of problem areas which require improvement are described in the following paragraphs.

4.2 MILITARY-SPECIFICATION RIGIDITY

4.2.1 Statement of Problem

Military specifications are too rigid. Furthermore, they do not keep up with the state of the art. In particular, they currently are not sufficiently specific to end-applications. One possible solution would be to modify them for classes of service.

4.2.2 Discussion

Military specifications are too rigid in that most adhere to a set pattern based on precedent rather than the needs of the user or changes in the state of the art. For example mechanical, environmental, and life tests found in

most military-semiconductor and microcircuit specifications are 10-15 years old. There has been no attempt to upgrade periodically the tests and the levels of severity that should be applied.

On the electrical end, MIL specifications are written broadly because in many instances the device end-application is not known. Therefore, presumably to be on the safe side a host of tests are included to encompass general-purpose applications.

Another encumbering factor is that in many instances a specification is broadly written to cover many suppliers. This weakens the impact of the specification and also serves to preserve the weakness by requiring the many suppliers to approve changes.

In components fabricated by high-volume production, the government must take the lead in the area of device specifications because any single industrial contractor would not exert enough economic influence to effect proper control.

4.2.3 Recommendations

- Try to limit the scope of specifications according to classes of service.
- Supply standard specification formats. These would be of help to the specification writer. These formats should be living documents subject to planned periodic change by a group of competent individuals with adequate device experience and laboratory back-up assigned to specification R & D.

4.3 APPLICATION AND USE

4.3.1 Statement of Problem

There are many factors influencing DoD device reliability which are related not only to device fabrication but also to device integration and operation in subsystems and systems operating in a field environment.

4.3.2 Discussion

DoD failure reporting and analysis techniques are sporadic. There is no good system whereby failed components are returned to a central establishment for sufficient failure analysis. Some failure information is reported to designers from the equipment fabrication and shakedown phases but little or none ever gets back from the field. There is a need for a better basis for relating failure to the design of the device, the circuit, the equipment, or the fabrication process.

The concept of life-cycle cost must be implemented. All too often the reliability of the equipment is sacrificed to minimize first costs. Reasonable trade-offs must be established to choose the proper first cost-reliability balance, thereby maximizing yield.

4.3.3 Recommendations

- One organization should supply competent support to assure that no interface problems arise during the application of devices to circuits and from circuits to higher levels of integration. Standard procedures must be developed to enhance the smooth integration of these parts.
- A practical system should be developed whereby timely feedback to the device designer is obtained from the equipment developers and users so that deficiencies in device design and fabrication can be rectified.

4.4 HIGH-VOLUME STANDARDS

4.4.1 Statement of Problem

It has been stated that, in order to increase reliability, devices used in government equipment should be related to high-volume production types. If production is not at a sufficient level for specific military requirement, the commercial specifications should be used for this application alone, if possible, to satisfy the military device requirements.

4.4.2 Discussion

Some of the advantages that may be attributed to the use of high-volume production devices are as follows:

Significantly lower prices are attainable due to higher yield and to economies of scale associated with liquidating development, setup, tooling and test equipment costs over a large base.

Commercial field experience is often available for use by government designers and purchasers in evaluating the risk of using commercial components. This engenders competition between would-be suppliers and assures multiple sources of supply.

Some of the disadvantages that may be cited for the use of high-volume commercial components are:

In order to qualify for military use, commercial production lines may require costly special design at both equipment and component levels. They may require the implementation of special screening procedures to assure compliance with more stringent military environmental requirements. These offset the potential cost advantage of the high-volume base.

Large-scale integrated circuits are considerably more specialized than devices of lower integration levels. Consequently, any policy designed to encourage the use of primarily commercially available integrated circuits could adversely limit the choices available to equipment designers and could also discourage future development of important large-scale integrated circuits.

The issue of standard, high-volume components versus custom-designed parts is not an easy one to resolve without further research and experience relating to specific cases. The introduction of integrated circuits in government equipment involves reliability risks at both the component and equipment levels. Whenever new processes are employed or new components are manufactured a learning period is encountered after the change of the manufacturing line. Once the learning interval has been passed, the line should be kept in operation in order to maintain high-yield performance. This is only practical if high-volume usage of the components exists. Custom devices having limited volume potential must bear a commensurate cost per unit and this additional cost must be reincurred whenever the line is restarted after an appreciable idle interval.

The use of high-volume commercial integrated circuits in military equipment is not without additional risk as to cost and reliability. Data have been accumulated that show that all complex electronic equipments go through a shake-down phase before desired reliability is achieved.* It is an open question whether equipment reliability improvement will be less costly when high-volume commercial components are used rather than custom-designed components.

4.4.3 Recommendation

Research and development programs should be undertaken to assess the cost-effectiveness of using standard, commercially available components, particularly large-scale integrated semiconductors, in different generic classes of equipment.

4.5 EFFECT ON YIELD OF EQUIPMENT RELIABILITY ENHANCEMENT

4.5.1 Statement of Problem

On occasion, the prediction and enhancement of equi ent reliability has been an R & D activity; and, thus, involved the services of s. scientific and engineering personnel. Generally, however, achievement of high reliability

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* J. D. Selby and S. G. Miller, "Reliability Planning and Management (rpm)" Paper presented at ASQC/SRE Seminar, Niagara Falls, New York 9/26/70.

has not been given sufficient priority during device, equipment, or system development. In the Apollo Program, reliability prediction, enhancement, and implementation was made the specific responsibility of a major subcontractor. As a result, hitherto unprecedented levels of system reliability were attained. In the past it has not generally been considered practical for economic reasons to achieve this high level of reliability in quantity-produced military devices and equipment. Reliability enhancement turns out to be principally a part of the manufacturing phase of equipment procurement. Consequently it may not receive adequate attention from persons with appropriate levels of competence. Moreover, a substantial effort to materially improve device, equipment and system performance or reduce equipment downtime, (and thereby greatly extend system operating life between overhauls) is seldom part of a procurement contract. Yet a significant increase in the field life of equipment between overhauls should be an easily attainable goal.

4.5.2 Discussion

There is a widespread tendency to procure devices and equipment on a lowest-cost basis, which is understandable and proper, other factors being equal. Unfortunately, the reflection of costs for reliability improvement works to the disservice of those manufacturers diligent in reliability upgrading. Although there is no guarantee that expensive devices or equipments are better than less costly products of the same kinds, it is important to recognize that reliability and performance of a high order are apt to be expensive and will tend to increase procurement costs. On the other hand, failure to make reliability a prime consideration may result in costs beyond measurement, e.g., as in an aborted or failed mission.

The Panel recommends that manufacturing contracts generally include funds earmarked for reliability prediction and enhancement. This allocation should cover the costs of performing a contractual commitment by the manufacturer to obtain performance and failure data from the field and to utilize such data for the improvement of product reliability. Such activities should be monitored by the personnel responsible for the original development or procurement. Follow-on orders for additional devices, equipment, or systems,

should be contingent upon the timely introduction of improvements derived from such reliability monitoring programs.

4.5.3 Recommendations

- Device, equipment, and system reliability enhancement should be recognized and documented as an essential activity by both supplier and user.
- Reliability-enhancement functions should be performed by highly qualified personnel.
- The enhancement of the reliability of devices, equipment, and systems should be a contractual part of the procurement.
- Field experience should be introduced into the procurement process with the aim of upgrading equipment or system reliability through the duty life cycle.
- Follow-on orders should require developmental improvements based on field performance and reliability data.

4.6 SCREENING AND BURN-IN

4.6.1 Statement of Problem

The mode and utility of screening and burn-in applied to military devices and subsystems have been debated. The DoD position relative to general application of screening and burn-in is not clear.

4.6.2 Discussion

Screening (nondestructive evaluation) and burn-in (operation at rated parameters for a stated period of time), as used here, are not meant to stress devices and subsystems beyond rated conditions.

Screening and burn-in at both the device and subsystem levels have proven useful. If these techniques are effective in screening out early defectives, they should be made mandatory on all components and subsystems procured by DoD.

At present, the preconditioning sequence to screening and burn-in is a fixed pattern of tests for all detail specifications based on test methods in MIL-STD-750 and MIL-STD-883.

4.6.3 Recommendation

Device and subsystem screening and burn-in should be studied as techniques for enhancing system yield and cost effectiveness.

4.7 DEVICE INTERCHANGEABILITY

4.7.1 Statement of Problem

Interchangeability of solid-state devices from different vendors is difficult due to variations in the design of the devices. This situation will probably worsen with the increasing complexity of integrated circuits.

4.7.2 Discussion

The principal reason given for the interchangeability problem is that component specifications tend to be overly oriented to vendor practices at the expense of user needs.

In many cases, the specifications are inadequate to ensure interchangeability of components. Some of the cited specification deficiencies are as follows:

> Parameters commonly accepted by various vendors tend to be included, ignoring others that are required but cannot be agreed upon between competing vendors. Thus, many specifications are incomplete.
>
> Specification limits are often deliberately widened in order to obtain greater yield from a given vendor, to accommodate process differences between vendors, or to reduce the cost

of testing. A reliability price is exacted for such increased tolerances, because of either greater power dissipation within the circuit or reduced parametric margins in the functional circuit.

The interchangeability problem becomes considerably more complex in the transition from discrete to integrated components. The two major reasons for this added complexity are:

There is a recondite and complex relationship, sometimes not yet analyzed, between individual element characteristics and circuit performance as measured at the terminals.

Some important properties of an integrated circuit may not be testable except under end-use conditions due to the large number of combinations of possible but unanticipated parasitic effects.

4.7.3 Recommendation

Specifications of integrated circuits should be based upon generic-use classes and oriented to the specifications of the user instead of the vendor.

CHAPTER 5

5.0 SYSTEMS APPLICATIONS AND USE*

5.1 INTRODUCTION

In Systems Applications and Use, the Panel focused its attention on the interaction between systems applications and the technical and economic factors involved in the procurement and production of microelectronic devices. The factors studied from a system point of view include:

- System mission as related to cost-reliability tradeoff
- System-design considerations
- Production and process controls
- Specifications and standards
- Qualification, screening, and acceptance procedures
- Failure-analysis techniques and procedures
- Procurement procedures and economic factors

5.2 BACKGROUND

5.2.1 Scope of Study

The past two decades have seen microelectronic technology grow from the laboratory to widespread applications in the full spectrum of electronic equipment employed by all the military services and NASA. These applications range from relatively straightforward types like the mass-produced mobile radio sets, utilizing off-the-shelf military-grade components, to highly sophisticated, low-volume missile, spacecraft, and aircraft subsystems wherein many of the individual components are custom designed, the manufacturing and testing processes scrupulously controlled, and system failure is considered catastrophic. The principal differences between the two extremes stem from economic factors that are strongly influenced by considerations of mission criticality, whether or not human life is at stake, maintenance philosophy, and ultimately the cost and prestige implications

*Consulting and editorial support for this Chapter, provided by Mr. W. J. Aston of the Aerospace Corporation, is acknowledged with thanks.

of failure. It was felt that any problems associated with the equipment on the lower end of the criticality scale (characterized by expected failures as reflected in MTBF calculations) were essentially traceable to the adequacy of existing component standards and specifications; these aspects have been treated in the chapter on Specifications and Standards. On the other hand, the Panel felt that the systems on the high end of the mission criticality scale, (characterized by the goal of zero failures) and perhaps most of the systems lying between the two extremes represented a significant problem area to be studied from a systems applications point of view. To this end, several major mission critical systems were investigated. The aim was to identify any specialized techniques, including novel technical and management approaches, that had been successful in achieving a much higher level of reliability than had been achieved in the other like systems.

5.2 2 Areas of Investigation

It was felt that examining the experience of several relevant major programs would be an effective way to study the problems of microelectronic applications to large systems and to learn of the various techniques used to ensure high reliability in these applications. Interviews were held with key government and contractor personnel familiar with the incorporation of microelectronics in the Apollo, Poseidon, Mariner, F-111 aircraft, Defense Support Satellite, and the AN/FYQ-47 Common Digitizer data-processing-system programs. While there exist a number of specifications, standards, technical reports, and procedures specifically dedicated to semiconductor and microelectronic components, it is also clear that merely using the military specifications in the placing of purchase orders is no guarantee of being able to consistently obtain devices of the quality and reliability specified. It is significant that many of these programs deemed it necessary to employ program management actions that worked outside of and beyond the standard procedures. Many of the methods used were quite similar in intent, but varied considerably in technique and implementation.

The Apollo program, for example, is widely recognized as a plateau in man's quest for technological systems superiority and is held as a considerable achievement in system reliability from which all other equipment development can now benefit. (Two case histories that illustrate the techniques used and benefits derived from planned integrated circuit high reliability in the Apollo Program are the paper prepared for this Panel by C. J. Godwin of the MITRE Corporation [(1)*] and the soon to be published paper by E. C. Hall of M.I.T. [(2)])

It should be remembered that the Apollo program received very high national priority, ample funding, and close to a decade in which to achieve operational capability. These factors do not diminish the significance of the Apollo achievement, but, when contrasted to typical military systems procurement, offer some cogent reasons for NASA's decision to adopt a parts development and qualification process tailored to its specific reliability needs. The military services, on the other hand, typically employ parts-development and qualification procedures that were created to satisfy the needs of the previous technological generation of military systems rather than today's technology.

Current practice in the DoD seems to substantiate the widely held viewpoint that not all programs can enjoy the same level of mission criticality or justify similar investment in component development or manufacturing techniques needed to attain a very high level of electronic reliability. Factors such as mission function and priority, available funding, operational safety, environmental requirements, and maintainability all influence the consideration of reliability-cost trade-offs at the system level, but exceptions occur. Thus, one finds select missile and space programs insisting upon the development and production of high-reliability electronic components while other DoD programs continue to struggle with field failures, aborted missions, extensive spare parts inventories, shortages of skilled maintenance technicians, etc. (The Rome Air Development Center prepared for the Panel a case history of the AN/FYQ-47 Common Digitizer program[(3)] which illustrates the significance of this problem and the approach taken by the USAF and FAA to achieve higher reliability in an advanced electronic ground system).

*Superscripts refer to references in 5.5, pp. 71, 72.

Knowledgeable people in the DoD are deeply concerned about the impact of microelectronic technology, and continue to seek assurance that higher reliability will ultimately lower overall systems costs without penalizing the performance of sophisticated new military systems.

The following comparison illustrates the integrated circuit procurement and application methods employed by two different kinds of programs, i.e., a "special" program in which high component reliability was needed to meet mission requirements, and a "typical" program in which more or less standard procedures and practices were used.

Characteristics of Special Priority Mission Reliability Program Versus Typical Priority Mission Reliability Program

Total Integrated Circuits Purchased

Special: 400,000 units

Typical: 10,000 units

Integrated Circuit Control

Special: Three circuit types

Typical: Ten circuit types

Integrated Circuit Qualification and Production Period

Special: Five years

Typical: Two years

Procurement Method

Special: a. Cost-type development contract

b. Fixed-price production contract

Typical: Vendor purchase order

Specifications

Special: Developed for program

Typical: Company preferred-part specifications modified for program

Vendor Selection and Qualification

Special:

a. Pilot production runs from three vendors under user surveillance

b. Electrical and reliability testing of pilot lots

c. Complete failure analysis and failure mechanism identification

Typical:

a. Electrical and physical test of small sample

b. Manufacturing line survey

c. Review of vendor-generated qualification data

d. Competitive bid

Vendor Monitoring and Control

Special:

a. User engineers direct monitoring of integrated circuit production interfacing with vendor manufacturing and engineering personnel

b. Cooperative problem-solving efforts during course of program

c. Baseline process specification changes controlled by user

Typical:

a. Defense Contract Administration Services or user quality assurance monitor lot acceptance testing

b. User engineers monitor preseal visual inspection

c. Occasional user visit to vendor plant, generally contacting a marketing representative.

d. Vendor provided user with a list of process specifications and a photograph of chip to define circuit

Lot Acceptance Testing

Special:

a. One hundred percent environmental, electrical, and burn-in testing with tight lot acceptance criteria; percent defective allowable less than 2%

b. Sample destructive physical test and examination

c. Analysis of all failures occurring during lot acceptance testing

d. Lot acceptance testing performed by user at user's facility.

Typical:

a. One hundred percent environmental, electrical, and burn-in testing based on military requirements and taking advantage of vendor's in-house testing system; lot acceptance based on a percent defective allowable less than 5%

b. Sample 100-hour life and destructive environmental tests with lot acceptance criteria; lot tolerance percent defective less than 10%

c. Acceptance testing done by vendor and monitored by user quality assurance or Defense Contract Administration Services

The special component-reliability program, outlined above, attained failure rates of about 0.003% per 1000 hours to a 90% confidence level. Guidance computers fabricated using these circuits have functioned without failure in numerous critical missions.

The integrated circuits procured by the typical program, outlined above, caused circuit board failure during equipment build-up. The cause of the problem was traced to defective metallization. All circuits were returned to the vendor, who instituted a crash corrective-action program that was apparently successful but could not be completely evaluated before launch. Specific screening for the metallization problem was performed on all replacement circuits; however, other failure mechanisms that might have been introduced by the corrective action could not be anticipated. The spacecraft was launched with a calculated reliability risk and is functioning properly, although insufficient operating time has been accumulated at this writing to verify system-reliability objectives. The integrated-circuit problem created serious project-scheduling delays, which contributed heavily to a cost overrun.

One of the principal areas of concern from a systems viewpoint is the question of whether or not the so-called high-reliability techniques are cost-effective. Another principal concern is the degree to which these techniques should be made applicable to more, or perhaps all, military electronic systems. The programs that have, of necessity, employed high-reliability techniques seem to demonstrate amply that these procedures, when properly applied, do, in fact, result in an outstanding level of reliability. The added increments of cost associated therewith are difficult to discern because of the various types of funding applied to the several research, development, test, and engineering (RDT&E) phases involved, and in no case was it apparent that the problem had been approached from the standpoint of evaluating higher component-reliability versus life-cycle costs. Since it appears that mission criticality is the key in determining whether high-reliability procedures and management techniques will be used, it seems logical that the DoD should re-examine their applicability to new military electronic systems.

5.3 SUMMARY OF FINDINGS

Examination of the application of integrated circuits to the various systems as outlined in the previous section, coupled with the personal and other experiences available to Panel members, clearly emphasizes the following two factors:

> First, typical system application, development and procurement procedures often result in less than satisfactory integrated circuit reliability. Though the initial cost of the integrated circuits may seem reasonable, the cost, schedule, and operational impact of failures at higher levels of assembly--or worse still, of field failures--leads one to the conclusion that improved techniques must be devised to ensure dependable high reliability at the component level.

> Second, some major critical programs have developed effective techniques for the application of integrated circuits that ensure a very high level of reliability. These techniques involve focusing management, engineering, and fiscal attention on reliability as a prime goal, a condition that would be impossible to achieve by the individual typical program by usual current practice.

The distinction between these two methods of system development and component procurement is predicated on an implicit understanding that various levels of criticality of mission function response enter into system conception, design, and acquisition. This is to say simply that not all hardware or software purchased for military use is equally critical as to end purpose, and therefore is not given the same level of treatment with respect to component specification and system development priority. These factors reflect down to the level of and set the philosophy for the procurement and incorporation of all electronic components used in a system.

This process of grading or judging the mission criticality of military equipment is described here as implicit because of the wide diversity of factors that, in the majority of systems programs, establish the requirements and the actual program character to obtain any particular level of equipment design quality and operational dependability. Overall mission function and the urgency for deployment of a system initially establishes a priority under which the program enters the design and acquisition cycle. In special programs (Polaris, Minuteman, Apollo), the level of funding and sustained urgency sets the program level of effort from the start and, in such exceptional programs, tends to define more explicitly the quality and reliability of electronic components, assemblies, subsystems, and systems. In the large majority of programs, however, more constrained budgets and less urgency are the case, and the end quality and dependability become largely dependent upon the soundness of the program design and its technological basis, the relative allocation of funding within elements of the program, the quality of program management, and the capabilities of the contractors selected to do the work. In the majority of programs the plan for component quality, reliability, and operational dependability, while possibly well conceived initially, must conform to rather rigid standard practices. Furthermore, in normal circumstances only an infrequent effort can be made to draw up special component specifications or make special adjustments. This differs in marked degree from the case of exceptional mission-critical programs.

It is clear that not all programs can be elevated in importance so as to command the funding and sustained effort in the component-acquisition program that is put into the few exceptional programs. The critical questions that arise are:

> Can each individual program apply at least some of the special techniques that the exceptional programs have so effectively used to ensure integrated-circuit reliability?
>
> Can DoD as a whole use its immense resources and purchasing power to achieve a very high level of reliability for all critical programs without burdening each individual program with a high cost in money and experienced talent

usually not available to the typical military system?

The Panel has addressed itself to these questions and has developed conclusions and recommendations that in some cases are far-reaching but, nevertheless, are believed to be implementable and would result in a great improvement in integrated-circuit yield and reliability for DoD systems.

5.4 DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

In developing the recommendations two factors were kept in mind. First, emphasis was placed on issues that would impact the technology fabrication and procurement of devices required in high-reliability applications. Second, the Panel was convinced that the problem of overall yield based on reliability is a serious one and therefore recommendations may have far-reaching implications in military system design and management. The intent of the recommendations is to serve as a goal and a point of departure for the conduct of a much more detailed analysis of the implications posed by the proposed solutions to this serious problem.

5.4.1 Systems-Applications Study

5.4.1.1 Discussion

In light of the limited scope of this study and absence of certain quantitative analyses and detailed comparisons, it was the Panel's feeling that some essential questions, including the following, required further analysis:

1. What is the total annual dollar value of the direct and indirect DoD and NASA microelectronic purchases and what percentage is this of the total dollar volume of the microelectronic industry? A breakdown of these numbers by circuit types, research and development, production, etc., should prove useful.

2. For a given number of DoD programs (perhaps ten), what is the cost of the integrated circuits and how does this relate to the overall system cost?

3. For several typical and special system-development programs, what are the costs involved in fixing problems arising in integrated-circuit applications that develop during system test? A comparison of all relevant factors among these programs should be made.

4. What is the optimum way to implement some or all of the recommendations gradually so as to maximize the long-term advantages and minimize the short-term pitfalls and dislocations that may result?

5.4.1.2 Conclusion

The Panel feels that an adequate study of the above questions would require the attention of highly qualified and experienced individuals both in and out of government with good judgment and a background in both the technical and management areas of DoD systems. Such a group of individuals could be motivated to undertake a quantitative study of the crucial factors that have been outlined, provided that DoD agrees on the value and necessity of the major thrust of the recommendations detailed below. The Panel feels that the results of such a study will validate the bulk of the recommendations, but strongly urges an intensive investigation to ensure that they are indeed valid and that the mode of implementation is the most effective.

5.4.1.3 Recommendation

The DoD should establish a committee or task group of highly qualified and experienced individuals, both in and out of government supported by full-time professional staff, to study the questions of 5.4.1.1, assess their implications,

and define options and optimum methods of implementation.

5.4.2 System-Design Considerations

5.4.2.1 Discussion

Generally, the work in early conceptual design assumes that new components can be procured in useful quantities that will show their predicted performance. Fabrication and production problems, and particularly the total end costs to obtain new components that consistently meet performance objectives and that will perform reliably in the system application, are often not fully appreciated early in a program's design phase. Frequently new components are designed into circuits and equipment primarily on the basis of needed performance--and premium prices are paid for the small quantities. Only if a problem as to availability of usable quantities or performance characteristics arises is attention really focused on the component design or on the status of the fabrication processes. Yield and quality factors are only of concern as they may affect availability for production use--not from the standpoint of fundamental quality, dependability, and and ultimate costs in end use. This larger concern is deferred to later in the manufacturing, acceptance, and field-testing phases and, as the intrinsic quality of the components emerge, unpleasant and costly experiences may often be the lot of the program.

While the discussion has generally considered current integrated-circuit technology along with other types of electronic components, the trend to large-scale integrated microcircuit assemblies will introduce special design factors into component procurement. These factors provide further pressures to use a limited number of circuit types, and can have beneficial effects in the larger sense on overall component standardization and quality and, ultimately, in systems reliability.

Experience in the Apollo and other programs has already shown that the selection of a few types of components with attendant concentration on all aspects of their development and manufacture can yield significant improvements in operational dependability.

It is true that the philosophy of limiting the types of components used in system designs is based on the standard-parts practice presently used. The result of applying these practices in military equipment design, however, has not been to limit the numbers of types of components used, but rather to set standards on a wide selection of components for reasons of logistics and support. Further, so-called nonstandard components are routinely incorporated into system designs because of the pressures to meet performance requirements derived from the system's mission requirements.[4].

5.4.2.2 Conclusion

Limiting the numbers of different microcircuit types that can be used in a particular system design relates to the presently used practices in standard components specifications, in that type limitation can effectively bound and force standardization. A large-scale move in DoD programs toward component types limitation should, in the long term, enable the purchase of better quality components. This is probably true for the reason that using fewer types of components in a design program should permit greater effort toward achieving standard levels of high reliability for all program applications. Reduced life cycle cost would probably be an added significant benefit.

5.4.2.3 Recommendation

Constrain systems design to the use of specific microcircuit types which have been developed, manufactured, and tested by techniques that will ensure high reliability. Limit and control the use of nonstandard devices to those applications where sufficient resources are available to permit an orderly development and qualification phase prior to inclusion in the system.

5.4.3 Specifications, Procedures, and Controls

5.4.3.1 Discussion

Early in its history NASA recognized the inherent advantages of employing microcircuits in high-reliability space applications, and sought ways of capitalizing on the then-burgeoning microelectronic technology. Each field

installation was, at that time, procuring and applying microcircuits on an independent basis without benefit of any NASA-wide specifications or standards describing performance characteristics, qualification tests, screen or acceptance tests, or other basic engineering documents. In response to this problem and to the urgent need for a cohesive and coordinated reliability program, NASA Headquarters embarked on a multifaceted plan(5) to provide a system of carefully defined surveys and evaluations, specifications, test, and data exchange methods. Now reasonably mature, this system attempts to provide NASA and its contractors the means of achieving uniformity in the procurement of microcircuits and information on qualified sources of supply. By its application, it is expected that procurement can be speeded up, duplication of effort and costs can be reduced, and high-reliability microcircuits can be developed and produced.

NASA has also utilized the concept of "line certification" as a means of ensuring that microcircuits for NASA programs are manufactured under conditions that have been demonstrated to be capable of continuously producing highly reliable products. This is accomplished by evaluating, in advance of production procurement, the manufacturer's capability for holding his own key processes within established limits at critical points and maintaining this capability during production(6).

The DoD has only recently begun writing military specifications for microcircuits, and military standards are not yet developed. This situation led the Military Operations Subcommittee of the House, in their recent study of the military supply system,(4) to conclude that "getting contractors to use selected or qualified items presupposes the existence and availability of useful listings of these items. If the specifications are out of date or nonexistent, it is futile to expect or demand that contractors use specified or standard parts. An essential element of the military standardization program is the development of usable specifications and standards." The Panel further concluded that "standards and specifications must be continually updated so that they reflect the latest advances in technology and the increasing performance and reliability requirements demanded

from contractors." The fact that military reliability requirements are increasing was emphasized by Dr. John Foster, Director of Defense Research and Engineering, in his recent testimony before the Senate Appropriations Committee (7) when he stated: "The dramatic advances being made in electronics technology gives us a major opportunity to...permit the development of ultrareliable equipment and systems (thousands versus hundreds of hours between failures) that will drastically reduce supporting logistics costs (maintenance personnel, spare parts inventory, training) and increase operational availability."

5.4.3.2 Conclusion

Microelectronics, because of the complex, advanced technology employed in their manufacture, must be controlled by a sophisticated and timely system of specifications, standards, process controls, and manufacturing test procedures. NASA has taken significant steps to accommodate this need for its own applications while the evidence indicates that the DoD has fallen behind in addressing the problem for military systems.

5.4.3.3 Recommendations

The DoD should convene a task group, or other suitable agency to develop and maintain detailed specifications, standards, and process control documents that will qualify microcircuits for use in military applications. The NASA system should be examined for applicability; however, it is not the recommendation of the Panel that the current NASA system be adopted. Rather, qualified individuals should evaluate its merits based on a more thorough study than was possible in this study. Microcircuit standardization efforts should be accelerated, with special emphasis placed on the achievement of a single high level of performance and reliability for all military applications. It is recognized that this is a difficult objective to achieve, but the potential benefits warrant a major effort. The Military Operations Subcommittee seems to share this view in their statement: "If a military service, or preferably the entire defense establishment, can cause a specified or standard item to be used in a variety of applications, the vendor often is able to offer it at a better price. It may then be cheaper to use the more sophisticated

item in all applications, rather than continuing to order various items with gradations of performance." [4]

5.4.4 Manufacture of Reliable Integrated Circuits

5.4.4.1 Discussion

Characteristic of all special programs studied was the recognition of the importance of establishment and control of a high-reliability integrated circuit manufacturing line. Although the degree of effort in this area varied with the size of the program (i.e., a very large program maintained a "captive" integrated circuit production line while a smaller program contracted for the manufacture of its integrated circuits in terms of specific processes, personnel, and facilities which had previously been qualified), the interest was clearly similar. It was to establish, through thorough evaluation, the reliability or quality of an integrated circuit produced by a given process and then to maintain the stability of that process throughout the actual production period.

It is interesting and significant that the definition of process control employed by these programs goes beyond the requirement for process documentation and technology certification (such as is contained in the General Military Specification for Microcircuits MIL-M-38510 and the NASA Line Certification Requirements for Microelectronics NHB-5300.4 (3C)[6] in that it recognizes the importance of stability in personnel, facilities, and production rate to integrated-circuit quality. In a report issued by the M.I.T. Instrumentation Laboratory [8] based on Apollo guidance computer experience, the adverse impact of seemingly innocuous process changes, personnel changes, and production discontinuity is discussed and illustrated, emphasizing the need for a stable and controlled production environment. The success of the Apollo program in procuring large quantities of reliable integrated circuits speaks favorably for this approach.

There is some discussion [9] as to what the optimum production rate (i.e., fewer than 10,000 versus more than 100,000 circuits per week) for a given high-reliability production line might be; however, there is no argument that some

rate must be established and maintained for a protracted period of time. In other words, it seems that in order to control the manufacture of integrated circuits to a high quality there has to be a willingness to commit to the procurement of a large quantity. While this represents no fundamental problem to the few major programs that require a large quantity, it is an insurmountable obstacle to the average DoD program. On the other hand, the sum total of all DoD small program integrated circuit requirements is numerically enough that controlled, reliable integrated circuit production to meet this requirement could economically be sustained. It was recently suggested in a report to the United States Congress(4) that if the requirement for high-reliability parts were large enough, the economics of the situation might cause certain manufacturers to convert to high-reliability manufacturing techniques for all parts produced. In this vein, it could be conjectured that by allowing the use of lower-quality integrated circuits in less critical applications, the DoD is destroying the high-reliability production base which could make it economically feasible to use a high-reliability integrated circuit in every DoD application.

5.4.4.2 Conclusion

Reliable integrated circuits are produced on tightly controlled and highly stable production lines. Since the establishment of such a line is beyond the scope of most individual DoD programs, they are not able to ensure the reliability of their integrated circuits. The DoD requirements for standard types of integrated circuits when considering the sum total of all program needs might be sufficiently large to allow for the economical establishment and maintenance of production lines.

5.4.4.3 Recommendation

The DoD should consider contracting with industry for the establishment and maintenance of high-reliability integrated-circuit production lines to produce a single quality of selected standard circuits for all military applications. Obviously, means must be found to consolidate DoD integrated circuit requirements and procurement methods such that production rates can be established that are consistent with program requirements.

5.4.5 DoD Management, Procurement, and Technical Surveillance

5.4.5.1 Discussion

Earlier in this report the Panel identified as a critical question: "Can DoD as a whole use its immense resources and purchasing power to achieve a very high level of reliability for all programs without burdening each individual program with the high cost in money and experienced talent which is usually not available to the "typical" military system?" The previous recommendations have focused on specific, tangible solutions based largely upon the experience of successful "special programs." What has not yet been addressed is the means of accomplishing these solutions in a manner that will reap the maximum benefits for the DoD and semiconductor industry as a whole.

The Panel was impressed that the successful programs were those that made maximum use of standardization in specifications, standards, process controls, management, and procurement procedures. Other "typical" programs appeared to suffer from the lack of standardization of these key elements, as well as insufficient purchasing power to impact the manufacturers adequately, and inadequate technical staffs to understand the technology and supervise the development and production of microelectronics properly for their programs.

The Defense Electronic Supply Center (DESC) does currently have the responsibility for centralized procurement of electronic components for in-house Defense Department requirements, particularly in the repair and maintenance fields. DESC appears to play no role in the procurement of electronic components for use by industry in the manufacture of military systems equipment. Our recommendation, therefore, implies a far more drastic change in the method of DoD technical surveillance, management, and procurement of microelectronic components than is involved in the DESC operation.

5.4.5.2 Conclusion

Consolidation of management, procurement, and technical surveillance by "special" programs has proved to be effective in obtaining highly reliable microelectronic components. Further consolidation, across programs and services, appears to hold the promise of achieving even greater progress toward the goal of maximizing total system cost effectiveness. The DoD appears to be in a singularly good position to accomplish this consolidation.

5.4.5.3 Recommendation

The DoD should study the feasibility of structuring a single agency, either within DoD or sponsored by DoD, with the authority and responsibility for consolidating the management, procurement, and technical surveillance of all microelectronics for military applications. Consideration should be given to inviting NASA participation and support in the study.

5.4.6 Microelectronic Research and Development

5.4.6.1 Discussion

The implementation of the above recommendations will of necessity tend to limit the system application of microelectronics to available circuit types with proven reliability and high volume usage. This will result in a dangerous inhibition of new technological developments that are essential for the improved performance of our military systems. A technique must therefore be developed that will encourage new and innovative state-of-the-art research and development, and a method must be devised to ensure the inclusion of reliability as an essential element in these microelectronic research and development programs. Furthermore, system program offices will have to be encouraged to make effective use of these state-of-the-art developments as appropriate.

5.4.6.2 Conclusion

New high-reliability microelectronic devices come into being through a concerted effort encompassing research and development, which includes reliability studies. To expect the majority of individual programs successfully to manage this

complex technological process is unrealistic because there are too many such programs and they are too small.

5.4.6.3 Recommendation

The DoD, with the assistance of the Advisory Group on Electron Devices, should establish avenues and controls for ensuring a continuing advancement in the state of the art in microelectronic devices, while simultaneously ensuring that only devices with demonstrated performance and reliability are permitted to be introduced into system applications.

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APPENDIX: CASE HISTORY

RELIABLE IC'S
A DO IT YOURSELF PROJECT

JUNE 1971

GENERAL ELECTRIC COMPANY
AEROSPACE ELECTRONIC SYSTEMS DEPARTMENT
UTICA, NEW YORK 13503

GENERAL ELECTRIC

RELIABLE I.C.'S - A DO IT YOURSELF PROJECT

June 1971

Presented By:

R. T. Simpson, Manager
R&QA Materials & Components

N.A. Scianna, Manager
Components Engineering

General Electric Company
Aircraft Equipment Division
Utica, New York

Reliable integrated circuits are readily available on the market today in that manufacturers are producing devices in sufficient quantities to satisfy our volume requirements. However, the placing of a purchase order alone, even with the most reputable sources, is no guarantee of being able of consistently obtain devices of the quality and reliability specified. In truth, that conclusion may be attached to any other purchased commodity. But for integrated circuits, the problem is magnified in that we, as a user, have been placing ever-increasing effort towards obtaining reliable devices (reference Figure 1). As a result, our procurement documents are more comprehensive, take longer to generate, and contain more supplier testing requirements than for any other commodity.

Our investment in incoming test facilities and the recurring test programming expenses are also proportionately greater for integrated circuits than for any other purchased commodity.

If reliable devices are available, then why as a user do we concentrate our technical resources in integrated circuit procurement?

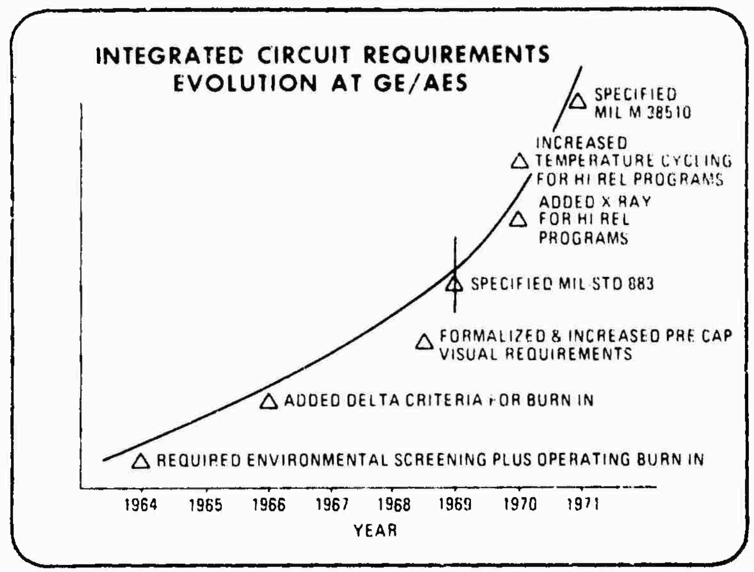

Figure 1

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The answer - that we must to achieve equipment reliability requirements - becomes clear in light of the problems that we have experienced.

Early in 1971, General Electric AESD compiled recent integrated circuit experience in order to assess technical procurement practices and procedures and to identify areas for improvements in specifications, procurement practices, quality and reliability.

The experiences accumulated were for integrated circuits procured to high reliability specifications and represent a point of view as a low volume consumer and original equipment manufacturer in the aerospace electronics business.

To establish the baseline for our data, it is first necessary to review our Technical Procurement Requirements (Figure 2) for integrated circuits and to emphasize that these requirements were negotiated with and accepted by the suppliers with attendant price increases.

It is also important to know that all of our experience is with supplier screened integrated circuits and, as will be shown later, to be with approximately 95% Bipolar Digital Devices. The production programs illustrated in Figure 2 vary in I.C. screening levels as we do not specify identical screening requirements for all devices procured. This is partly due to the evaluation of equipment reliability requirements versus screening effectiveness and cost. However, the primary reason is the dynamic evolution of more stringent reliability screening techniques and their documentation vehicles (e.g., MIL-STD-883). Due to configuration control requirements, production equipments are not always able to immediately take advantage of these developments.

As part of our procurement specifications we require that suppliers provide screening data (Figure 3) with every shipment. Not only does this data help us assess the kinds of problems experienced by the supplier on a given lot, it also provides objective evidence that specified tests were actually performed.

INTEGRATED CIRCUIT SCREENING - SUPPLIER REQUIREMENTS

REQUIREMENT	CONDITIONS	CURRENT PRODUCTION PROGRAMS			
		DATA PROCESSING	SPACE	SURV RADAR	ECM
TEMPERATURE STORAGE	150 200°C 24 HRS	X	X	X	X
TEMPERATURE CYCLING 5	55 65°C to +150 200°C	X			
10				X	X
20			X		
CENTRIFUGE	20KG MIN	X	X	X	X
GROSS AND FINE LEAK	5 x 10 TO 1 x 10	X	X	X	X
BURN IN GO NO GO	168 HOURS 125 C OPERATING	X			
DELTA LIMITS			X	X	X
LOT JEOPARDY		X	X	X	X
PRE CAP VISUAL SUPPLIER CRITERIA		X			
MIL STD 883 COND A	METHOD 2010.1		X		
COND B				X	X
RADIOGRAPHIC MIL STD 883	MIL STD 750		X*		

Figure 2

INTEGRATED CIRCUIT DATA REQUIRED FROM SUPPLIERS

- PRODUCTION HISTORY
  - INITIAL LOT QUANTITY
  - TOTAL QUANTITY AVAILABLE FOR SHIPMENT
  - QUANTITIES SHIPPED PREVIOUSLY
- BURN-IN TEST
  - DEVICES TESTED
  - CATASTROPHIC FAILURES
  - PARAMETRIC FAILURES (GROUP A LIMITS)
  - DELTA FAILURES
- OUTGOING QUALITY
  - QUANTITY INSPECTED
  - ELECTRICAL REJECTS
    - QUANTITY FOR EACH REJECT MODE
  - MECHANICAL REJECTS
    - QUANTITY FOR EACH REJECT MODE

Figure 3

Some business statistics will help to complete the background picture. In 1970, seven major I.C. industry suppliers provided 95% of the 300,000 devices we procured with two of them together providing approximately 75%. We would also like to point out that the following data represent a cross section of our experience with the industry singling out no one supplier.

SUMMING UP QUALITY

Integrated circuit quality as measured on receipt at Incoming Test and Inspection has shown considerable overall improvement during the time period between 1968 and 1970. (Figure 4)

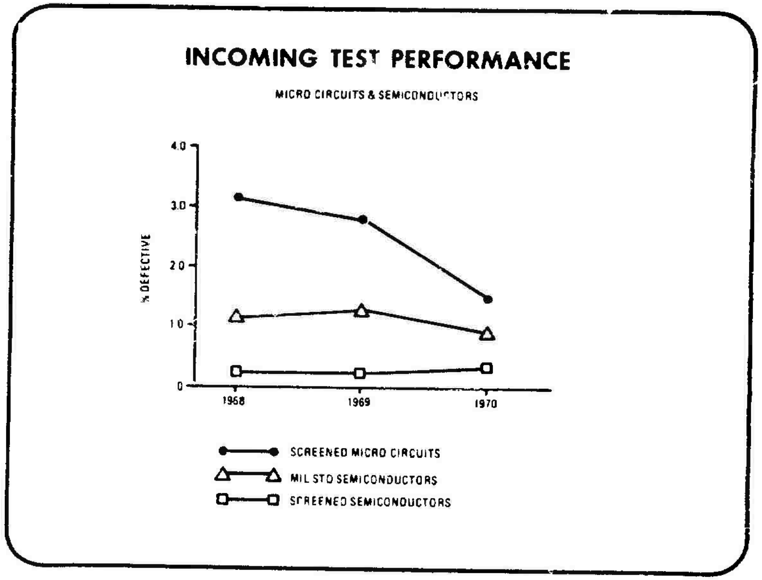

Figure 4

We believe that this incoming improvement is the result of two significant factors: 1) The evolution of the tighter screening requirements previously described that we have placed on the suppliers, and 2) Real device reliability growth caused by the suppliers factoring corrective action into device design, improved processes, and better process controls.

Notwithstanding the reason, the improvement is impressive, particularly in that we have generally tightened and improved our incoming test in this same time frame.

Looking at the same chart we see that the incoming test performance for screened semiconductors has been consistent and at a low level relative to microcircuits during this same time period. As we have specified and paid for 100% screened and tested material, we see no acceptable reason for the higher test rejection rate for microcircuits.

A quick look at our incoming electrical test practices (Figure 5) shows that both integrated circuits and semiconductors are 100% tested. For the digital devices comprising 95% by volume of the microcircuits tested, we utilize automatic, tape programmed test equipment taking measurements under ambient temperature conditions.

The results of this testing are portrayed in Figure 6. An across-the-board look at the data shows that the majority of rejections are the result of a few basic measurements falling outside of specification limits. Worthy of note is that we still find catastrophic failures among 100% screened and tested devices.

Incoming quality measurement is incomplete without considering mechanical inspection performance. Figure 7 summarizes our 1970 findings which are the result of visual inspection on a lot sampling basis. The problems identified are fundamental and attributed to lack of supplier attention to detail in both process and quality control. Aside from the schedule and cost problems associated with these basic reasons for rejection, the rejection which bothers us the most is the 17.2% of the total attributed to vendor data. In this category, we have accounted for devices rejected because the supplier test data provided disclosed that the devices shipped did

INCOMING ELECTRICAL TEST PRACTICES

SEMI CONDUCTOR DEVICES	% TESTED	PARAMETERS MEASURED
DIGITAL INTEGRATED CIRCUITS	100	D C PARAMETERS PROPAGATION TIME RISE AND FALL TIME PULSE WIDTHS
LINEAR INTEGRATED CIRCUITS	100	PD POWER DISSIPATION AV VOLTAGE GAIN BW BANDWIDTH VOUT - OUTPUT VOLTAGE SWING CMREJ - COMMON MODE REJECTION IB - INPUT BIAS CURRENT IID - INPUT OFFSET CURRENT VOO - OUTPUT OFFSET VOLTAGE
TRANSISTORS	100	BVebo, BVcbo, BVceo, BVcer Icbo, Iebo, Iceo, Icex hfe, Hfe, ft Vbe, Vce, Vcb Vbe sat, Vce sat, Vcb sat Idd, Igs, Vgs (Field Effect Transistors)
DIODES	100	IF, VF, BV Vz, Vf, Ir, Zzt, Zzk (Zener Devices)

Figure 5

INCOMING ELECTRICAL REJECTIONS - 1970

TRANSISTORS REJECTION	% OF TOTAL		DIODES REJECTION	% OF TOTAL		INTEGRATED CIRCUITS REJECTION	% OF TOTAL	
BREAKDOWN VOLTAGE	22.9		LEAKAGE CURRENT	41.4		SWITCHING PARAMETERS	31.7	
LEAKAGE CURRENT	19.9	62.7%	FORWARD VOLTAGE	15.8	71.5%	LEAKAGE CURRENT	24.8	80.1%
D C GAIN	19.9		OPENS	14.3		LOGIC LEVELS	23.6	
OPENS	17.1		BREAKDOWN VOLTAGE	13.5		CURRENT DRAIN	10.7	
SHORTS	10.1		SHORTS	9.0		CATASTROPHIC	4.4	
SATURATION VOLTAGE	8.9		ZENER VOLTAGE	2.2		OUTPUT VOLTAGE (REGULATOR DEVICES)	4.2	
OTHER	1.2		OTHER	3.8		OTHER	6	

Figure 6

INCOMING MECHANICAL REJECTIONS - 1970

REJECTION	TRANSISTORS		DIODES		I.C.'S	
	PERCENT OF TOTAL					
COMMON						
MARKING	34.7		65.6		17.2	
CARRIER MOUNTING	14.8	64.2%	4.7	76.6%	28.2	56.3%
LEADS DAMAGED	14.7		6.3		10.9	
LEAD PLATING	6.3		4.7		10.9	
WRONG PART	5.3		10.9		9.4	
DIMENSIONS	7.4		4.7		6.2	
SPECIFIC						
LEADS CONTAMINATED	8.4					
HEAT SINK ASSEMBLY	8.4					
BREAKAGE			3.1			
VENDOR DATA (10% LOT JEOPARDY)					17.2	

Figure 7

not meet our screening specifications. This is attributed to communication breakdown in the supplier's plant as well as lack of attention to detail.

Not included in our 1970 data summary is the impact of MIL-STD-883, Method 2010.1, Internal Visual (Precap) on our incoming mechanical inspection results. Late in 1970, we initiated a sample de-cap visual inspection at Incoming to verify supplier workmanship quality. This was initiated due to device failures in equipment which, when analyzed, disclosed supplier workmanship failing to meet MIL-STD-883 precap visual criteria. The initial lot subjected to a de-cap inspection at Incoming was rejected. The results of our de-cap inspection to date are summarized in Figure 8. These results are not encouraging in that we are only submitting lots to de-cap inspection where we are paying the supplier for 100% precap inspection to MIL-STD-883

INCOMING INSPECTION - IC DECAP VISUAL

MIL STD 883 METHOD 2010 : CONDITION A

LTS

INSPECTED	LOT QTY	SAMPLES INSPECTED	REJECTED		
			SAMPLES	LOTS	% OF LOTS INSPECTED
82	39000	228	15	10	12

ONS FOR REJECTION

OREIGN MAT L	OXIDE & DIFFUSION	METALIZATION	SCRIBING & DIE	BONDING
3	1	4	1	1

PERIOD 9/70 4/71

Figure 8

1970 - INCOMING EXPERIENCE INTEGRATED CIRCUITS

VOLUME -- PERCENT OF TOTAL

TYPE	%	VOLUME PIECES	REJECT RATE ELEC.	REJECT RATE MECH.
LOGIC GATE	42.6	125,360	1.6	2.5
FLIP-FLOP	23.7	73.732	.8	5.9
BUFFER	20.6	64,200	2.3	.2
GENERAL	6.1	17,919	1.6	8.2
OPERATIONAL AMP.	2.7	8,040	1.0	.3
LOGIC GATE EXPANDER	2.4	7,120	.1	.4
LINEAR AMP.	1.6	4,740	13.8	0
ADDER SUBTRACTOR	.2	517	2.9	13.8
SHIFT REGISTER	.1	206	.5	14.6

TOTAL	AVG. REJECT RATE ELEC.	AVG. REJECT RATE MECH.
301,834	1.5	3.9

Figure 9

In a recent incident, two in-process failed devices were failure analyzed and found grossly unacceptable to the precap visual criteria of MIL-STD-883. Investigation with the supplier disclosed that the lot had been sample precap inspected to the supplier's criteria instead of the 100% to the MIL-STD as required by our specification. The supplier is replacing the entire lot free of charge.

In another incident, fortunately a random occurrence, a device clearly labeled with MIL-STD-883 identification was discovered at Incoming Inspection with its cover offset from the f... e, resulting in an unsealed device.

Accumulating and summing up our 1970 data (Figure 9) shows that we experienced a 1.5% electrical and 3.9% mechanical rejection rate.

Now, having established the magnitude of the overall problem with averages, let's look at it dimensioned another way. The first view (Figure 10) is performance of a supplier from March of 1968 to December 1970 for a single device type. Each lot received is represented by a point on the chart. Thirty-one of the 49 or over 60% of the lots received contained no test failures. The other lots ranged from approximately 1 to 10% defective. Let's look at another device which was purchased from three suppliers in grossly the same time frame (Figure 11). Again, the dots on the chart represent lots received containing zero test failures. As we didn't make changes to purchase specifications or incoming test acceptance standards that contributed to these results we can only attribute the variation to the supplier's periodic lapse in control over outgoing quality.

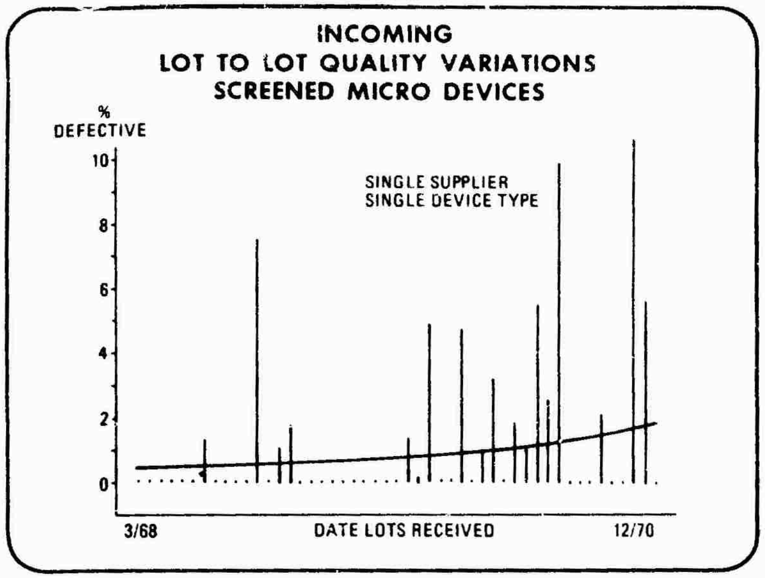

Figure 10

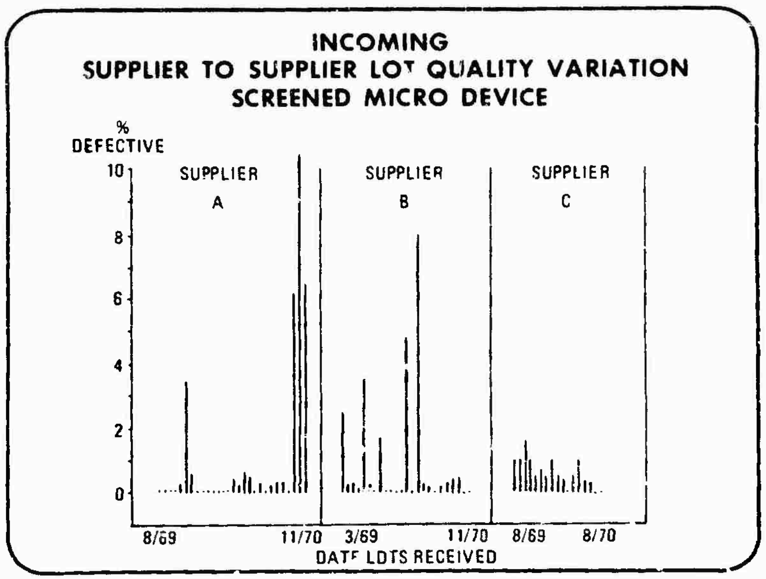

Figure 11

Having observed the sporadic problem of receipt of lots of unacceptable quality, we see no reason why the average incoming rejection rate experienced for integrated circuits cannot be significantly improved through proven quality control practices readily available to industry suppliers.

No technical breakthroughs are needed here. Until the industry establishes adequate control over outgoing quality, we recommend and will conduct an incoming test program as our most cost effective means of screening the material received and to assure the timely identification and correction of problems.

PUTTING I.C.'S TO THE TEST

After supplier and incoming screening, integrated circuits are considered acceptable for further processing. They are stored, handled, assembled, soldered, cleaned, tested and tested again. Testing takes place at all assembly levels from board through system reliability demonstration and includes the entire spectrum of environmental testing. On programs using a large number of integrated circuits, modules are subjected to both low and high temperature screening ranging from -60° C to +85° C before unit burn-in. Units are burned in typically for 50-100 hours at temperatures of -35° C to +65° C. Later systems are subjected to environmental testing including both vibration and temperature cycling.

Integrated circuits failed during all these testing programs at the rate of three primary failures per thousand devices processed during 1970. Figure 12 shows how integrated circuits fared as a group compared with other part types. The factors which must be considered in evaluating the I.C. ranking on this chart are that I.C.'s are the only part group which is 100% screened by the supplier and I.C.'s, transistors and diodes are the only groups 100% tested at Incoming. Ignoring complexity and just based on all the previous screening alone, I.C.'s should be the lowest failure rate group on this chart. The fact that they aren't raises questions which need answering.

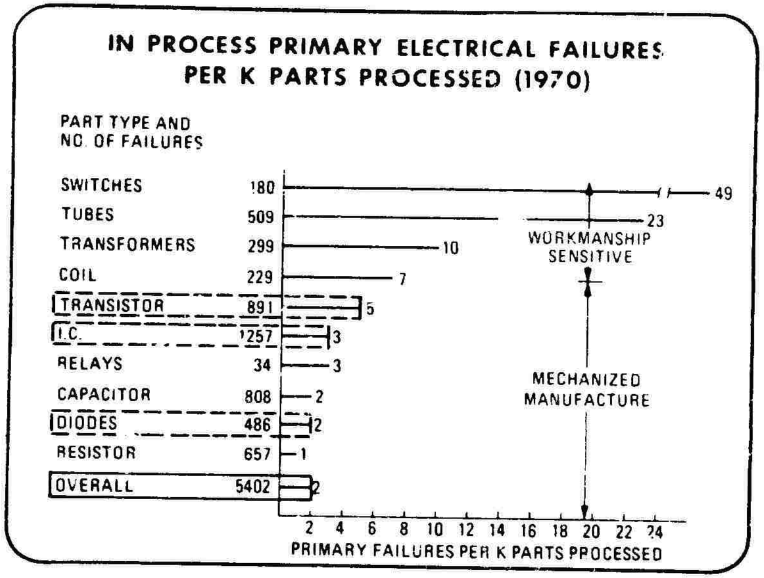

Figure 12

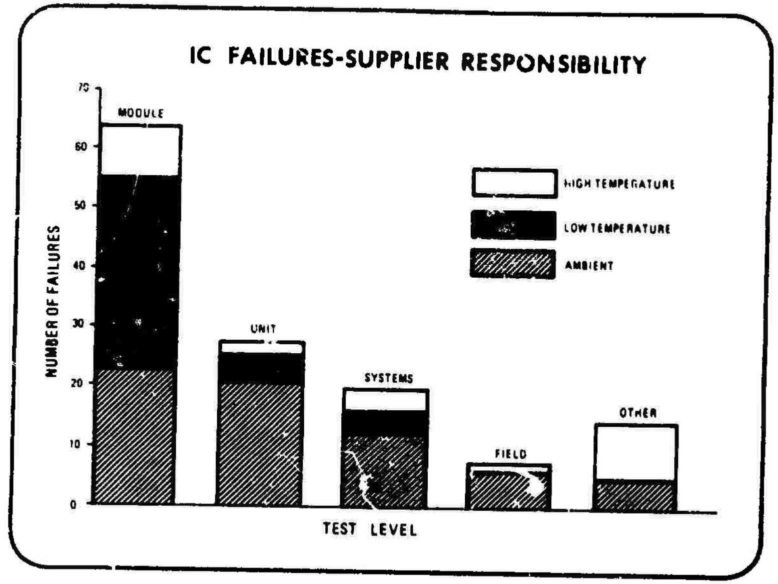

Figure 13

One of the first questions is where and under what conditions did the devices fail? To answer this we looked at some selected data. It was selected in that it included only those failures which we had confirmed through failure analysis and had assigned responsibility to the supplier. Figure 13 shows the distribution of supplier fault failures during in-process testing.

A significant percentage of the failures occur at first level test (48%) either during or subsequent to initial in-house temperature exposure. Although there is a sharp drop between module and unit testing, it still requires these additional test levels with their corresponding increases in device operating time to screen these failures out of the equipment.

The field data on this chart cannot be considered representative of the population of all devices shipped due to limited field data and visibility, but it does establish that devices failing for supplier responsibility still escape all current screens.

In depth failure analysis provides us with greater visibility and many of the answers needed. The summary of I.C. failure analysis (Figure 14) starts focusing in on the problems. In 1970 we analyzed 410 selected I.C. failures. They were selected by Product Area Quality and Reliability Engineers based on the need for more information in order to establish effective correction action plans. In 1970 our failure analysis laboratory was able to confirm 5% more of the failures received than in 1969 reflecting both improved selection procedures and laboratory techniques. In the supplier responsibility area, we identified what appears to be an encouraging trend. The net improvement over 1969 is almost 12%, and if workmanship is considered alone, there is a favorable variance of 14%. This trend tracks the improvement we identified earlier in the on receipt quality as measured at

SUMMARY OF IC FAILURE ANALYSES
1969 vs 197C

FAILURE ANALYSES		1969 QUANTITY	1969 % OF TOTAL	1970 QUANTITY	1970 % OF TOTAL	% OF CHANGE
TOTAL VERIFIED		287	66.8	293	72.0	+5.2
TOTAL TEST OK		143	33.2	117	28.0	5.2
TOTAL CONDUCTED		430	100.0	410	100.0	0
VERIFIED FAILURE RESPONSIBILITY						
SUPPLIER	DESIGN	NA	NA	7	2.4	2.4
	WORKMANSHIP	161	56.1	123	42.0	14.1
AES	DESIGN	NA	NA	1	.3	+ .3
	WORKMANSHIP	4	1.4	1	.3	1.1
	TESTING	91	31.7	101	34.5	+ 2.8
MISC	UNDETERMINED	19	6.6	58	19.8	+13.2
	OTHER	12	4.2	2	.7	3.5
TOTAL VERIFIED FAILURES		287	100.0	293	100.0	0

Figure 14

electrical test. (Reference Figure 4.) But proceeding cautiously and looking at the miscellaneous category we found we lost some ground in our ability to assign responsibility. Failures for undetermined causes rose by 13% to what appears to be an unsatisfactory level. There are two basic reasons for the rise in this category. The first is by being conservative in assignment of supplier responsibility and the second is a decision not to pursue the evaluation due to either the limits of our analysis capability, or the time and cost involved supported by the knowledge that there is no pattern of failures associated with the failed device.

Now having identified 130 supplier responsible failures, we have narrowed the field down to an area that we would like to get our arms around. Figure 15 describes the major categories and distribution of failure mechanisms associated with this group of failures.

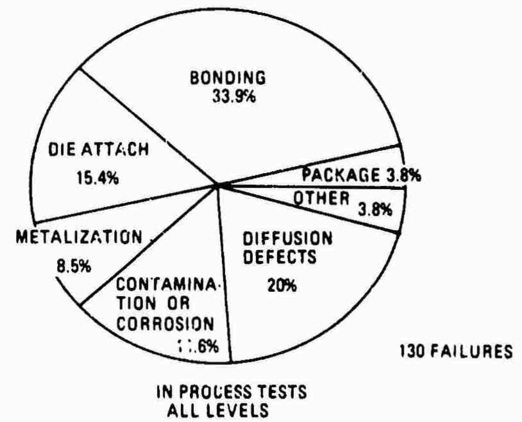

Figure 15

This chart tells us that the causes for the failures are assignable and are consistent with other known data. Bonding defects stand out as the most frequent cause of failure and as such have caused adjustments to our reliability screens.

Probing further and with 20-20 hindsight vision (Figure 16) gives us an analysis of whether or not these failures should have been detected using MIL-STD-883, Method 2010 1 Internal Visual Inspection criteria. Our evaluation is that in almost 38% of the cases, the answer is a definite yes with only 16% being a definite no. This data contributed to our decision to place greater emphasis on verifying the adequacy of supplier precap visual inspection through an incoming de-cap inspection described earlier.

1970 IC SUPPLIER FAULT REVIEW

SUPPLIER FAULTS THAT SHOULD BE DETECTED WITH MIL-STD-883 METHOD 2010.1 INTERNAL VISUAL

SUPPLIER	YES DEFINITE	YES QUESTIONABLE	NO DEFINITE	NO QUESTIONABLE	TOTAL
A	9	3	6	3	21
B	15	2	4	22	43
C	1	0	1	18	20
D	7	0	6	7	20
E	0	0	1	0	1
F	15	2	2	3	22
G	2	0	1	0	3
H	0	0	0	0	0
TOTAL	49	7	21	53	130
%	37.7	5.4	16.2	40.7	100.0

Figure 16

1970 SIGNIFICANT IC PROBLEMS

PROBLEM DEVICE	SUP	CORRECTIVE ACTION
● LIFTED DIE OTL FAMILY	F	A) REPLACED PYROCERAM WITH ALLOY (AU SI EUTECTIC) BONDING B) REPLACED METAL PACKAGE WITH CERAMIC PACKAGE C) REPLACED SUPPLIER
T²L AND OTL FAMILY	C	ADDED ROVING INSPECTOR PLUS TIGHTENED CRITERIA FOR DIE LIFT DIE SHEAR AND CONTAMINATION
● CORROSION WIRE CONTAMINATION (CHLORINATED LUBRICANTS; OTL DEVICES	A,B, C,F	CHANGED TO HIGHER PURITY WIRE WHICH USES A DIFFERENT LUBRICANT
INSUFFICIENT CLEANING OTL DEVICES	F	MINIMIZED THE USE OF CONTAMINATING CHEMICALS AND IMPROVED CLEANING PROCEDURES
ORGANIC BINDER USE IN SEALING COMPOUND	B	CHANGED PACKAGE WHICH DOES NOT REQUIRE ORGANIC BINDER
● OXIDE/DIFFUSION DEFECTS OTL DEVICES	A	ADDITIONAL CLEANING BEFORE AND IMPROVED DRYING CYCLE AFTER CONVERSION COATING USE OF SIPHONIC RINSING
OTL DEVICES	C	TIGHTER PROCESS CONTROL AND INSPECTION ADDED ELECTRICAL TESTING

Figure 17

As added inspection is only a tollgate on the road to responsible corrective action, it is our practice to feed back our failure analysis findings to the involved supplier.

Figure 17 shows some of the problems experienced and the corrective actions reported by the suppliers. The problems experienced were not limited to one supplier. In these areas five suppliers were involved with four shown as having a common corrosion problem. In brief, all suppliers shown with these problems responded to our analysis findings with corrective action.

Overall 1970 corrective action results from failure analysis are shown in Figure 18. This identifies by supplier the type of action reportedly instituted. Basically, these actions can be reduced to design or process changes, and additional tests and inspections. No one corrective action was found that has the same effectiveness in every instance with the exception of dropping the supplier's approval (our action), which is done only when all else fails to produce results.

Our evaluation of the actions taken indicated 15% of the problems eliminated and 50% significantly reduced. In that we are a low volume consumer of devices, it is rewarding to know that our feedback of problems helped cause actions to be taken to improve integrated circuit quality and reliability.

Reviewing some of the data already discussed and pulling it together provides the picture shown in Figure 19. This provides only a view of our internal experience with integrated circuits in that supplier and field data are not included.

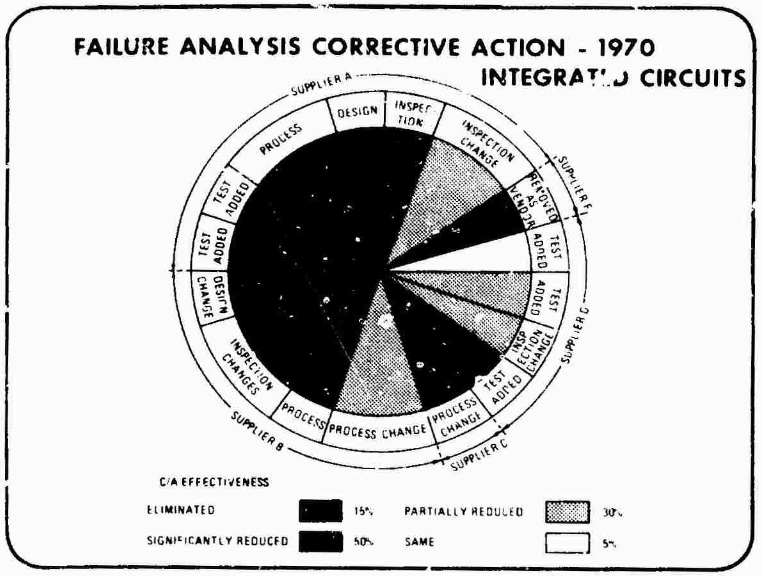

Figure 18

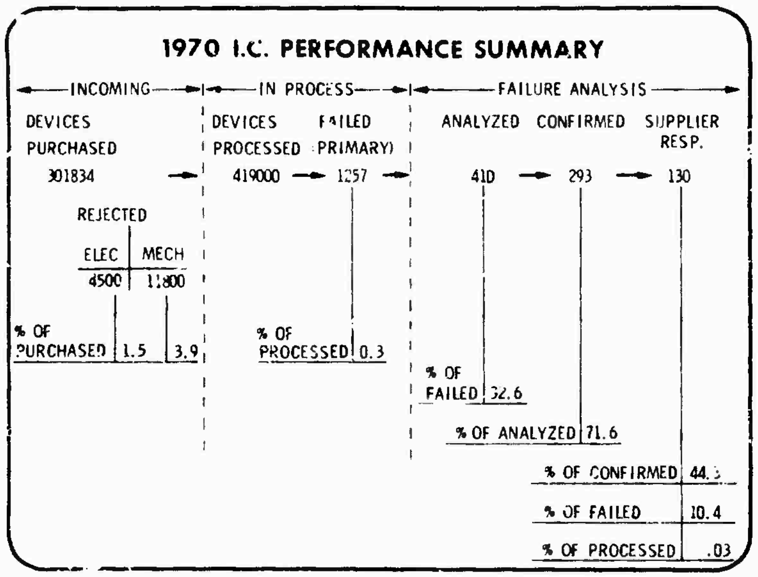

Figure 19

Here the pay-off of incoming test and inspection is clear. Imagine the cost of troubleshooting, repairing, and retesting to find and fix an additional 4500 devices during the in process cycle. Limiting this rationale to electrical test rejects assumes that almost 12,000 mechanically rejected devices might not have caused a significant in-process problem.

Moving over to the failure analysis area and looking at the 130 supplier responsibility failures amounting to 0.03% of the devices processed, it is easy to be convinced that this is a respectable number.

Remembering what we learned through failure analysis tells us otherwise. These failures were precipitated with additional temperature cycling, could have been detected with existing precap visual inspection standards and can be eliminated or significantly reduced by corrective action within the state-of-art.

Converting the data obtained into failure rates per million device hours and adding in available supplier and field data we obtained the picture portrayed in Figure 20.

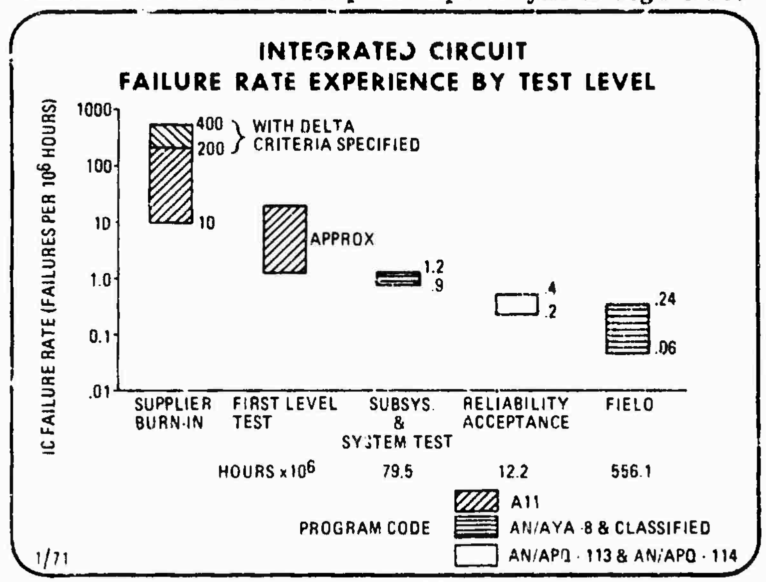

Figure 20

From the data provided by our suppliers we learned that failure rates in device burn-in ranged from a low of 10 to as high as 400 failures per million hours when Delta drift criteria were specified. The effectiveness of screening at this level is dramatic.

The screening contribution of first level testing is estimated as the records maintained do not include device hours.

Moving to subsystem and system test results, we see that on two programs consisting of over 79 million device hours we experienced failure rates ranging from 0.9 to 1.2 failures per million hours.

On another program for two configurations of the same system where we had a reliability demonstration requirement, we experienced failure rates as low as 0.2 to 0.4 failures per million hours.

The field experience shown is for equipment having end use applications in relatively benign environments, and receiving above-average care in handling and use.

The failure rate improvement shown doesn't just happen. It is the result of a planned quality and reliability program oriented towards early detection and correction of device related problems. Investment in facilities, personnel, and planning is required for all test levels from Incoming through in-process to identify and isolate problem devices.

In fact, the effort necessary to be expended on integrated circuits by the user to achieve equipment reliability requirements could be described as a "Do It Yourself Project."

IN CONCLUSION

We are convinced by equipment performance that reliable I.C.'s are available, but have concluded from our experience that it is still necessary to allocate significant technical resources to their procurement and testing.

I.C. reliability progress is apparent as shown by favorable trends in both our Incoming Test and Failure Analysis data. We believe that continued reliability improvement is necessary and that significant improvement can be achieved without technical breakthroughs.

Closer control of quality by suppliers, including adherence to the existing specifications, will eliminate many of the problems we have experienced including the one of on receipt lot-to-lot quality variation.

In addition, positive correction actions being developed from failure analysis findings and factored into specifications, designs, processes and testing screens will bring needed reliability improvement.

Although encouraged by the evident supplier progress, I.C. reliability performance still depends to a large measure on the strength of user commitments.